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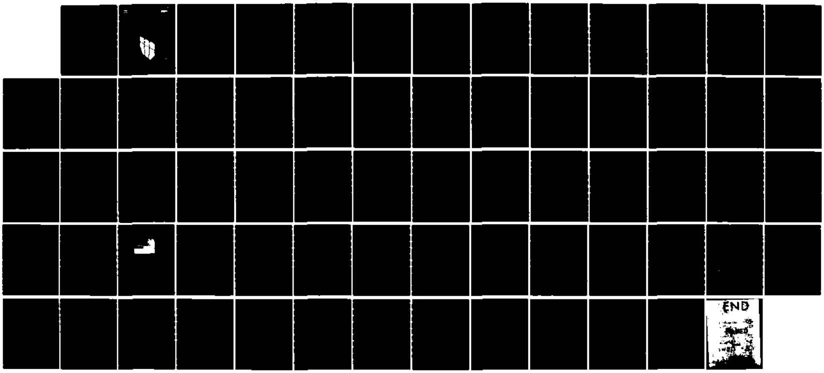

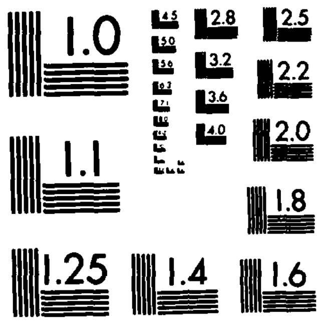
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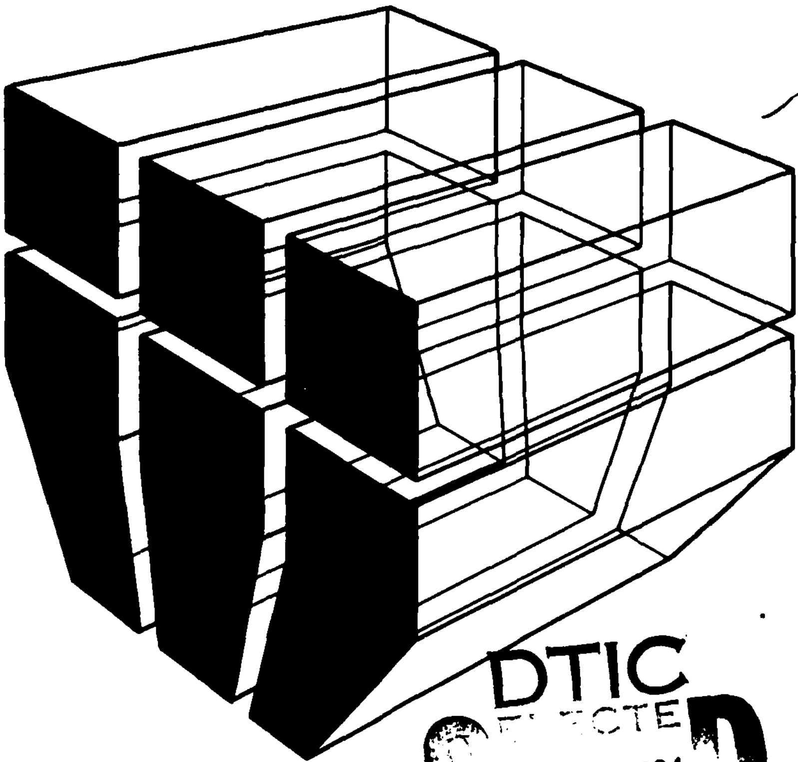
June 1984

LANDFILL LINERS AND COVERS: PROPERTIES AND APPLICATION TO ARMY LANDFILLS



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Leachate produced by buried waste often must be totally contained to prevent groundwater and surface water contamination. Landfill gases must be similarly controlled to reduce the risk of explosion or asphyxiation at nearby structures. Liners and covers used at Army sanitary landfills can prevent the production and migration of landfill leachate as well as migration of gas outside refuse boundaries. Information is provided to help Army installations choose landfill liner and cover systems resistant to chemical attack from the leachate generated and compatible with the environment. (Continued)

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A liner and cover system must be designed with consideration of pollution regulations, environment, climate, and type of leachate produced. Federal regulations requiring the landfill to comply with the most stringent local air and water quality standards are summarized.

The material used as a liner or cover must also be chosen based on the environment, climate, and chemical compatibility with the leachate. Both natural and synthetic materials are available and each type must be expected to react differently with the leachate produced at a given site. Natural materials include clays and soils--either local or transported from another location. Synthetic membranes include various manmade polymers that are seamed at the fill site to form a giant pouch to contain the leachate. In a separate class are asphalts and admixed materials; these may be either sprayed onto landfill walls or applied as with highway construction.

A liner and cover system may include piping, additional gas controls, and adjacent lagoons for collection, treatment, or recycling. The system should have monitoring devices or sampling points, as the landfill's continued success depends on careful control throughout the service life and after closure. Examples are cited of landfill sites actually using complete liner and cover systems.

FOREWORD

This work was performed by the Environmental (EN) Division of the U.S. Army Construction Engineering Research Laboratory (CERL) for the Directorate of Engineering and Construction, Office of the Chief of Engineers (OCE), under Project 4A762720A896, "Environmental Quality Technology"; Technical Area A, "Installation Environmental Management Strategy"; Work Unit 033, "Sanitary Landfill Leachate Control at Military Installations." The OCE Technical Monitor was Walter Medding, DAEN-ECE-G.

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COL Paul J. Theuer is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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LANDFILL LINERS AND COVERS: PROPERTIES AND APPLICATION TO ARMY LANDFILLS

1 INTRODUCTION

Background

The burial of waste (landfilling) has been a widely accepted method of disposal for many years. U.S. Department of the Army (DA) sanitary landfills can be unique in that waste from military operations (e.g., chemical warfare training residues, propellant, explosive, or pyrotechnic residues, abandoned transformers) may have entered a land disposal site by inclusion in the general solid waste stream.

Natural processes occurring in the buried waste can transform and mobilize its constituents into a liquid effluent called leachate. Rain and surface water infiltration compounds the problem. Anaerobic decomposition of the refuse also generates gases, mainly carbon dioxide and methane, which can migrate into structures built on or near the landfill. This situation is dangerous because of the explosive hazard due to the methane, and because the gases can displace air in enclosed areas and asphyxiate occupants.

The use of low permeability materials to cover solid waste landfills on DA installations is a feasible method of preventing rain and surface water infiltration. Such materials can also be used to line the bottoms and sides of these impoundments to prevent leachate from leaking out and contaminating groundwater or surface water as well as to prevent moisture from entering the fill.

The Resource Conservation and Recovery Act of 1976 (RCRA) has mandated that the Environmental Protection Agency (EPA) inventory all landfill disposal sites in the United States. State agencies must classify solid waste disposal sites as either dumps or sanitary landfills. Abandoned and operating land disposal sites (authorized and unauthorized) are found on almost all DA installations. Many of these sites could be classified as open dumps; however, the use of liners and covers can upgrade these landfills to comply with State and Federal regulations.

Objective

The objective of this report is to provide Army installations, Major Commands (MACOMS), and Districts with information on current landfill regulations and preliminary guidelines for the selection and installation of liners and covers at Army sanitary landfills.

Approach

An extensive literature survey was performed, and information related to the different liner and cover properties was summarized. Military installations were visited. Pilot and full scale tests of different liner and cover applications were evaluated, then lessons learned from existing landfill operations were compiled.

Mode of Technology Transfer

It is recommended that the information in this report be used to update AR 420-47, Solid Waste Management; TM 5-634, Refuse Collection and Disposal; and TM 5-814-5, Sanitary Landfill.[1]

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[1]Army Regulation (AR) 420-47, Solid Waste Management (U.S. Department of the Army, August 1977); Technical Manual (TM) 5-634, Refuse Collection and Disposal (U.S. Department of the Army, July 1958); TM 5-814-5, Sanitary Landfill (U.S. Department of the Army, August 1983).

2 LEGAL REQUIREMENTS FOR POLLUTION CONTROL AT ARMY DISPOSAL SITES

The major Federal regulations for controlling pollution and the effects of landfill leachate and gas are based on legal requirements of the RCRA (as amended) (Public Law [PL] 94-580), the Federal Water Pollution Control Act (FWPCA) (as amended) (PL 92-500), and the Safe Drinking Water Act (SDWA) (as amended) (PL 93-523). RCRA is the basis of three separate Federal regulations for landfill selection, operation, and closure.

Section 40 of the Code of Federal Regulations (CFR), Part 241 (revised July 1, 1979), "Guidelines for the Land Disposal of Solid Wastes," lists required and recommended procedures for designing and operating a sanitary landfill. Required activities include compliance with the most stringent local air and water quality standards by proper site selection, design, and operation.

The recommended procedures are far more comprehensive. For selection and design, complete hydrologic and geologic evaluations of a proposed landfill site are recommended as well as consideration of proposed land use plans for adjacent areas. Recommended procedures for protecting water quality include monitoring wells, leachate treatment and control systems, guarding against 50-year floods, and infiltration minimization systems. Recommended gas control procedures include systems for gas collection, gas venting, and explosion prevention. Recommended recordkeeping practices include records of leachate and gas sampling, ground/surface water sampling, and quantitative measures of types and locations of solid wastes buried in the landfill. Most state regulations for landfill sites list the recommended procedures of Part 241 as requirements for obtaining an operating permit but, to date, no state has adopted all the recommended procedures. States typically regulate site location, cover material, and recordkeeping. At the state agency's discretion, leachate, water quality, and gas analyses may be required.

Section 40 CFR, Part 257, "Criteria for the Classification of Solid Waste Disposal Facilities and Practices," gives minimum criteria for classifying a land disposal site as a sanitary landfill. Failure to meet these criteria results in an "open dump" classification, which requires either upgrading to the sanitary fill criteria or closure. The regulations stipulate the following: no landfill sites in 100-year floodplain areas without proper precautions related to flow restriction, water storage, and washout of solid waste; no surface water contamination resulting in a National Pollutant Discharge Elimination System (NPDES) violation, 404 permit violation, or 208 permit violation; no groundwater contamination beyond landfill boundaries exceeding NPDES; and no explosive gas concentrations exceeding 25 percent of the lower explosive limit (LEL) of methane. The regulations also list criteria for new landfill sites and expansion of existing sites beyond original planned boundaries. Basically, the regulations require an approved solid waste management plan; evaluation of the site's hydrogeologic condition; volume and chemical and physical properties of the leachate and gas produced; baseline quality of surface water and groundwater supplies; location of existing and alternate drinking water supplies; and a complete evaluation of the site's effects on public health. Under the regulation, EPA will, after approval of a state solid waste management plan, grant enforcement authority to the states. This section also outlines a permit procedure.

Section 40 CFR Part 250, "Hazardous Waste Guidelines and Regulations," lists the criteria for classifying wastes as hazardous and for designing and operating a hazardous waste landfill. These regulations do not deal directly with a typical municipal-type landfill except when the landfill's leachate is classified as hazardous. EPA considers leachate hazardous when it exceeds 100 times the national drinking water standards (40 CFR 216.24). Classification of a landfill's leachate as hazardous radically changes landfill operation, including leachate monitoring, collection, treatment, and prevention.

The FWPCA is the basis for two sets of regulations: the NPDES and the National Water Quality Criteria (NWQC). The NPDES applies to leachate collected and discharged at one or more points. Basically, this is a permit system specifying the type, concentration, and amount of pollutants that can be discharged into surface water from a single point. The NWQC specifies the minimum quality allowed for surface water systems (streams, rivers, and lakes). Under these criteria, pollution sources must maintain the quality of the receiving water, and the types and amounts of pollutants they can discharge are regulated.

The SDWA is the source of the National Primary Drinking Water Standards (NPDWS). Table 1 lists the current standards. Surface or groundwater sources exceeding these standards will require extensive treatment to remove the offending pollutant(s). The pollutant sources contaminating these supplies will probably be forced to develop expensive treatment systems. The NPDWS also serve as one of the bases for classifying waste as hazardous (40 CFR, Part 250) and for evaluating water pollution effects from landfill operations (40 CFR, Parts 241 and 257).

Most regulations cover existing or proposed landfills; very few regulations currently govern closed or abandoned landfill sites. The states and the EPA are taking a comprehensive inventory of existing and closed landfills. Historically, closed sites have only been important when a gas or leachate problem occurs. Regulations will probably be approved soon, however, that require gas and leachate monitoring of an offending closed landfill site for up to 15 years after closure. A few state regulations require gas monitoring in buildings near or on old landfill sites as well as groundwater and surface water monitoring on closed, leaching landfills.

Table 1

National Interim Primary Drinking Water Regulations:
Maximum Contaminant Levels (MCL) for Inorganic Chemicals*

Contaminant	Levels (mg/L)
Arsenic	0.05
Barium	1.0
Cadmium	0.010
Chromium	0.05
Lead	0.05
Mercury	0.002
Nitrate (as N)	10.0
Selenium	0.01
Silver	0.05
Fluoride	**

MCL for Organic Chemicals

Contaminant	Levels (mg/L)
Endrin	0.0002
Lindane	0.004
Methoxychlor	0.1
Toxaphene	0.05
Chlorophenoxys	
2-4, D	0.1
2,4,5-TP Silvex	0.01

Proposed Regulations for Additional Maximum
Contaminant Levels

Contaminant or Condition	Level (mg/L unless specified otherwise)
Chloride	250
Color	15 (color units)
Copper	1
Foaming agents	0.5
Iron	0.3
Odor	3 (threshold odor number)
pH	6.5-8.5 (pH units)
Sulfate	250
Total dissolved solids	500
Zinc	5

*Source: Federal Register, Vol 44, No. 179 (13 September 1979).
**40 CFR, Part 257 should be consulted for these MCL determinations.

3 ENGINEERING PROPERTIES OF LANDFILL LINERS AND COVERS

Design Considerations for Liners

Liners are natural or synthetic materials used to cover the walls and floor of a landfill. Leachate produced by a landfill site may have to be totally contained inside the landfill at sites where hydrogeologic conditions threaten contamination of ground and surface waters. As part of a collection, recycle, or treatment strategy, the liner must provide an impervious barrier to hold any leachate produced until the liquid is collected and treated. Therefore, it should be able to resist physical and chemical attack by the leachate.

The environment in which the liner must perform changes, depending on the treatment strategy employed; thus, methods of installation also differ. For example, the type of control scheme planned will determine whether an underdrain system must be installed before the liner is placed.

The strength of the leachate and the length of time the liner is exposed to it also differ with alternative treatment strategies. For example, a landfill with no leachage treatment or recycle scheme that incorporates a liner and a cover designed to eliminate infiltration of surface and rainwater would be expected to have low-volume, high-strength leachate. A site using a leachate treatment and recycle process would be expected to have high-volume, low-strength leachate. Therefore, the chemical compatibility of the liner and leachate must be considered for each different situation if the liner's integrity is to be maintained.

Design Considerations for Covers

A surface cover is a natural or synthetic barrier placed over the top of a landfill to keep contaminants in and precipitation out. Three types of surface covers--daily, intermediate, and final--are used during and after landfill operations. The type of cover used depends on the length of exposure to the elements. The minimum thickness and exposure time for the three cover types are presented in Table 2.

Daily cover, which is used to control vector, litter, fire, and moisture problems, typically is placed at the end of the working day. If possible, however, the cover should be spread and compacted as the refuse cell is formed so that only a working face needs covering at the end of the day. Intermediate cover is also placed daily, but may be stronger to act as a temporary road base and provide a limited barrier to gas migration. Final cover is placed after landfilling is complete. It should help seal in contaminants and prevent moisture from entering the buried refuse. Depending on the site's ultimate use, the final cover may be designed to support various loads without significant settlement, permit vegetative growth, and control any hazardous landfill gas migration.

Table 2

Application of Cover Material*

Cover Material	Minimum Thickness	Exposure Time (Days)**
Daily	6 in.	0-7
Intermediate	1 ft	7-365
Final	2 ft	365

*Source: D. R. Brunner and D. J. Keller, Sanitary Landfill Design and Operation, Environmental Protection Publication SW-65ts (Solid Waste Management Series, EPA, 1971).
**Length of time cover will be exposed to erosion by wind and rain.

A landfill cover's role differs, depending on the leachate and gas control system used. Therefore, the amount and type of infiltration and gas controls needed must be considered in cover design. For example, a design that would allow the infiltration required for a leachate recycle system might not be consistent with a cover system designed to control vertical migration of gas. The type or amount of infiltration control needed will depend on the control strategy used. However, in most cases this will be a qualitative, not quantitative measurement. If a quantitative measurement is needed, then a landfill water balance must be conducted, including moisture content of the refuse, precipitation, and all factors affecting runoff and infiltration. An example in which a water balance might be helpful would be in determining the potential moisture-holding capacity of a landfill when a leachate recycling system is being considered.

Variations in weather conditions throughout the year must also be considered in cover design. Earth covers can become saturated and frozen in some climates, which would impede both infiltration and vertical gas migration. In more temperate climates, however, natural covers could be considered because their engineering properties would be more consistent.

Choice of Materials for Liners and Covers

Either natural or synthetic material can be used for liners and covers with each type having distinct advantages and disadvantages (Tables 3 and 4). Natural materials include clays and soils; synthetic membranes are made of materials such as polyethylene (PE), polyvinyl chloride (PVC), butyl rubber, ethylene propylene diene monomer (EPDM), chlorinated polyethylene (CPE), and others. Asphalts and admixtures of native soil with either montmorillonite or cement are also used as covers and liners. In general, materials used as liners and covers should have a permeability of 1×10^{-7} cm/s or less.

Table 3

Advantages, Disadvantages, and Restrictions of Using Synthetic and Natural Liner Materials*

Material	Advantages	Disadvantages	Restrictions
Clay	If available on-site or nearby, more economical. Can be designed to self-seal if penetrated.	May crack under differential settling and weathering. Must be kept moist. Traffic movement may be a problem.	Can only be installed before landfilling. Performance must be monitored.
Synthetic materials	May be necessary in areas where clay is unavailable or if landfill leachate is not compatible with clay liner.	Relatively expensive. May interact adversely with leachate, causing failure.	Can only be installed before landfilling. Performance must be monitored.

Table 4

Advantages, Disadvantages, and Restrictions of Using Synthetic and Clay Capping Materials*

Material	Advantages	Disadvantages	Restrictions
Clay or high clay content soil	Economically preferable in areas where clay is available.	Fine-grained clays may dry and crack seasonsally. Maintenance required to keep clay moist and to prevent plants with deep root systems from penetrating cap.	Must be combined with grading and planting and be effective.
Synthetic materials	When clay is not available or transportation costs are excessive may be economically preferable.	Routine maintenance necessary as described above. Easily punctured. Relatively expensive.	Careful grading and planting must be done.

*Source: C. Wiegand, G. Gerdes, and B. Donahue, Alternatives for Upgrading or Closing Army Landfills Classified as Open Dumps, Technical Report N-123/ADA113371 (U.S. Army Construction Engineering Research Laboratory [CERL], 1982).

The designer of a solid waste landfill must choose liner and cover materials based on a wide range of requirements. First, factors in each site's soil and geology must be known if several sites are being considered. It is necessary to consider the membrane as part of a layered system extending from the waste through the liner and subgrade to the soil base and the aquifer being protected. The cover can be considered the same way, starting with the vegetative cover and topsoil layer through the membrane cover to the supporting subgrade and finally the waste.

Factors that should be investigated when choosing a liner material include:

- Type of waste and leachate composition
- Type of soils and subsoils near site
- Groundwater chemical composition
- Hydrology and groundwater elevation at site
- Climate
- Permeability of soil or subsoil
- Compatibility of native soils with waste leachate
- Compatibility of liner materials and seams with waste leachate
- Costs of materials and installation.

The type of waste to be disposed of in the landfill is most important. The unique types of waste at Army installations should be identified and compatibility with the liner material should be studied.

The soil types available on site should be investigated for possible use since local soils are usually the least expensive material. The soil's plastic and liquid limits with water and with the waste leachate also should be determined, and its structural strength is important in providing subgrade support for the liner. The site's groundwater level and hydrology must be considered, because a rising or falling groundwater table can cause ballooning of the liner (discussed further in Chapter 5). The permeability and thickness of the soil and subsoil also influence liner choice as do other physicochemical properties of the subsoil.

Climatological factors such as temperature and rainfall can affect a liner's performance. In addition, membrane liner installation can be hindered by hot or cold temperatures that make membranes too stretchy or too brittle. Rainfall can make seaming difficult or impossible.

Besides the factors just described, the relative ease of installation, quality control, repair, and maintenance for the liner should be considered. If all design requirements are met, the choice will be based on the cost of the material and installation. Table 5 summarizes properties, costs, advantages, and disadvantages of different liner materials.

Table 5

Summary of Liner Types*

Liner material	Properties	Range of Costs**	Advantages	Disadvantages
Soils:				
Compacted clay	Compacted mixture of onsite soils to a permeability of 10^{-7} cm/sec	L	High cation exchange capacity; resistant to many types of leachate	Organic or inorganic acids or bases can solubilize parts of clay structure
Soil-bentonite	Compacted mixture of onsite soil, water and bentonite	L	High cation exchange capacity; resistant to many types of leachate	Organic or inorganic acids or bases can solubilize parts of clay structure
Admixes:				
Asphalt-concrete	Mixtures of asphalt, cement and high quality mineral aggregate	M	Resistant to water and effects of weather extremes; stable on side slopes; resistant to acids, bases, and inorganic salts	Not resistant to organic solvents; partially or wholly soluble in hydrocarbons; does not have good resistance to inorganic chemicals; high gas permeability
Asphalt-membrane	Core layer of brown asphalt blended with mineral fillers and reinforcing fibers	M	Flexible enough to conform to irregularities in subgrade; resistant to acids, bases, and inorganic salts	Ages rapidly in hot climates; not resistant to organic solvents, particularly hydrocarbons
Soil asphalt	Compacted mixture of asphalt, water, and selected in-place soils	L	Resistant to acids, bases, and salts	Not resistant to organic solvents, particularly hydrocarbons
Soil cement	Compacted mixture of Portland cement, water, and selected in-place soils	L	Good weathering in wet-dry/freeze-thaw cycles; can resist moderate amount of alkali, organics and inorganic salts	Degraded by highly acidic environments
Polymeric membranes				
Butyl rubber	Copolymer of isobutylene with small amounts of isoprene	M	Low gas and water vapor permeability; thermal stability; only slightly affected by oxygenated solvents and other polar liquids	Highly swollen by hydrocarbon solvents and petroleum oils; difficult to seam and repair
Chlorinated polyethylene	Produced by chemical reaction between chlorine and high density polyethylene	M	Good tensile strength and elongation strength; resistant to many inorganics	Swells in presence of aromatic hydrocarbons and oils

*Source: Hazardous Waste Land Disposal/Land Treatment Facilities, Preliminary Draft (Department of the Army, Huntsville Division, [illegible], 1983). Adapted from Technologies and Management Strategies for Hazardous Waste Control, Office of Technology Assessment, Congress of the United States, 1983 (noncopyrighted). Used with permission.

**L -$1 to $4 installed costs per sq yd in 1981 dollars; M - $4 to $8 per sq yd; H - $8 to $12 per sq yd.

Table 5 (Cont'd).

Liner material	Properties	Range of Costs**	Advantages	Disadvantages
Chlorosulfonated polyethylene	Family of polymers prepared by reacting polyethylene with chlorine and sulfur dioxide	H	Good resistance to ozone, heat, acids, and alkalis	Tends to harden on aging; low tensile strength; tendency to shrink from exposure to sunlight; poor resistance to oil
Elasticized polyolefins	Blend of rubbery and crystalline polyolefins	L	Low density; highly resistant to weathering, alkalis, and acids	Difficulties with low temperatures and oils
Epichlorohydrin rubbers	Saturated high molecular weight, aliphatic polyethers with chloromethyl side chains	M	Good tensile and tear strength, thermal stability; low rate of gas and vapor permeability; resistant to ozone and weathering; resistant to hydrocarbons, solvents, fuels, and oils	None reported
Ethylene propylene rubber	Family of terpolymers of ethylene, propylene, and nonconjugated hydrocarbon	M	Resistant to dilute concentrations of acids, alkalis, silicates, phosphates and brine; tolerates extreme temperatures; flexible at low temperatures; excellent resistance to weather and ultraviolet exposure	Not recommended for petroleum solvents or halogenated solvents
Neoprene	Synthetic rubber based on chloroprene	H	Resistant to oils, weathering, ozone, and ultraviolet radiation; resistant to puncture, abrasion, and mechanical damage	None reported
Polymeric membranes				
Polyethylene	Thermoplastic polymer based on ethylene	L	Superior resistance to oils, solvents, and permeation by water vapor and gases	Not recommended for exposure to weathering and ultraviolet light
Polyvinyl chloride	Produced in roll form in various widths and thicknesses; polymerization of vinyl chloride monomer	L	Good resistance to inorganics; good tensile, elongation, puncture, and abrasion-resistant properties; wide range of physical properties	Attacked by many organics, including hydrocarbons, solvents and oils; not recommended for exposure to weathering and ultraviolet light
Thermoplastic elastomers	Relatively new class of polymeric materials ranging from highly polar to nonpolar	M	Excellent oil, fuel, and water resistance with high tensile strength and excellent resistance to weathering and ozone	None reported

Factors that should be investigated when choosing a cover material include:

- Type of soils and subsoils near site
- Possibility of erosion from surface runoff
- Climate
- Cover function related to infiltration
- Cover function related to gas movement
- Reliability and sensitivity of material to weathering
- Costs of material and installation.

Again the soils and subsoils on site should first be studied for use as cover material to provide an impermeable membrane and support a vegetative cover. Eliminating surface water with diversion ditches or increased surface slope can help control infiltration and thus influences the choice of cover material. The use of soils or subsoils to line diversion ditches is also a possibility. Using additives, blending other soils for better gradation, increasing thickness, and compacting all reduce infiltration as well. Also, using a layered system or a membrane barrier helps keep water out of landfills. If infiltration is to be allowed, such as in a recycling system, it can be assisted by reducing the surface slope, using permeable soil, or eliminating compaction.

Gas movement through the cover can be controlled by using a very fine soil such as clay and by maintaining a high degree of saturation. A membrane barrier can also be installed to eliminate gas migration through the cover. If it is decided to allow gas migration through the cover to discourage off-site lateral migration, a coarse, granular cover soil can be used or gas vents can be installed.

Climate is very important in determining how a cover material will perform. For example, in dry climates a soil that does not crack may perform better than a clay. Membrane barriers used as covers should be studied for resistance to sunlight or other weathering. Again, if all other factors are equal, costs can be used to determine the choice of material.

Maintenance of Lined and Covered Solid Waste Landfills

Proper management of a solid waste landfill is very important to achieving maximum effectiveness of a liner or cover and is provided for in the design. If the disposal facility's integrity is to be protected, the liner and cover system performance should be monitored, including the groundwater or drainage system below the liner, pipes or vents through the cover, and, in the case of recycling, the level and composition of leachate above the liner. The liner and cover system's physical condition should also be inspected for abnormal swelling, degradation, or other changes.

Several standard procedures are used for operation and maintenance of solid waste landfills. For lined and covered landfills, additional information should be included in the operations manual to reflect the specific type of material and construction used. This information should be obtained from the designers and construction specialists who installed the system and should include details about the system's components. Quality control data and "as-built" drawings should be obtained and samples of the liner and cover materials should be retained for use in case of failure. The material's limitations and, for liners, a list of compounds incompatible with the material are very important.

The waste composition must be controlled to avoid damage to the liner. It is assumed that hazardous materials will be excluded from a sanitary landfill; however, an additional requirement is to avoid materials that will attack the liner. The compatibility of incoming waste with the wastes in the landfill also should be assured. Landfill operators should be aware of the types of industrial, process, or specialty wastes that might be placed in the landfill and their compatibilities with the liner. Liquids or sludges to be buried in the landfill should be chemically treated and mixed with the municipal solid waste, soil, or a suitable dry absorbent to eliminate any free flowing wastes. Records should be kept of the wastes placed in the landfill, including a list of any organic or inorganic constituents that could be aggressive to the liner.

It is very important to inspect the landfill regularly. Any inadequacies in the liner or cover, such as an exposed cover, should be reported at once. Preventive maintenance should be practiced as well; for example, vehicle passage over an exposed liner or cover should always be avoided. Gas vents also should be inspected for plugging and the integrity of piping through the cover and liner should be checked.

Damage observed on a liner or cover should be repaired as soon as possible to avoid a massive failure. Openings in the liner or a failure in the anchor trench can damage the earthwork below. An exposed membrane cover can degrade, leaving a weak spot in the cover system.

Vegetation around the landfill perimeter and under the liner should be eliminated. Damage can result if weed growth begins under the liner, and weeds along the anchor trench or side slopes can penetrate the liner with their roots. Also, if vegetation is to be planted on a cover, specialized short-rooted varieties should be used to protect the cover's integrity.

Rodents such as gophers, squirrels, rats, and mice can damage a liner or cover if their path to food or water is blocked. In addition, certain ground squirrels are known to eat PVC materials.

Differential settlement can result in ponding and increased infiltration, so depressions should be filled as soon as possible. Vandalism and unauthorized dumping should also be controlled. Since liner and cover technology is relatively new with limited basic knowledge and experience, records should be kept detailing the system's performance as well as any failures.

4 NATURAL MATERIALS AS LINERS AND COVERS

Characteristics of Soils and Clays

In soil mechanics, the soil mass is considered to consist of solid particles and spaces that fill with air and water. The basic weight and volume relationships of the soil components can be derived using Figure 1. The more important parameters used in soil engineering include unit weight (density), void ratio, porosity, and degree of saturation. These relationships are based on the weight and volume of wet and dry soil specimens and the specific gravity of the solids.[2] By definition:

- Dry unit weight (γd) or dry density--weight of oven-dried soil solids per unit of total volume of soil mass. Usually expressed in kilograms per cubic meter.

- Wet unit weight (γm) or wet density--weight (solids plus water) per unit total volume of soil mass, irrespective of the degree of saturation (see below). The wet unit weight is usually expressed in kilograms per cubic meter.

- Void ratio (e)--ratio of the volume of voids to the volume of solid particles in a given soil mass.

- Porosity (n)--ratio (usually expressed as a percentage) of the volume of voids of a given soil mass to the total volume of the soil mass.

- Degree of saturation (S)--ratio (usually expressed as a percentage) of the volume of water in a given soil mass to the total volume of voids.

Another important characteristic of the soil is the water content, (w). Water content is expressed as either a ratio of the weight of water to the weight of solid material or the volume of water to the total volume of the soil mass.[3]

The Atterberg limits are a frequently used, empirical characterization for soils which describe the consistency and mechanical behavior of clayey soils, with each type's mechanical behavior. These limits are based on soil consistency and different moisture contents. Each limit is defined by the water content that produces a specified consistency (Table 6). Used alone, the Atterberg limits mean little; however, when used as an index to the relative properties of clay-type soils, they are very helpful.[4]

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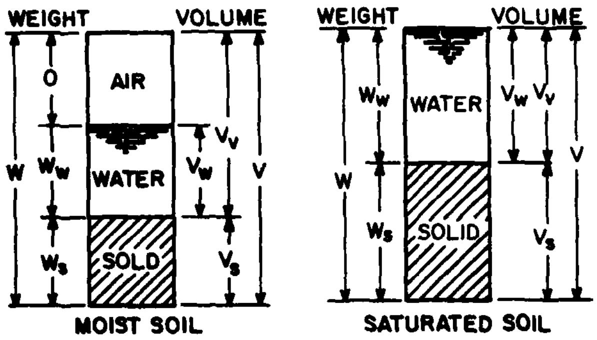
[2] Engineer Manual 1110-2-1906, Laboratory Soils Testing (U.S. Army Corps of Engineers [USACE], 1970).
[3] R. J. Lutton, G. T. Regan, and L. W. Jones, Design and Construction of Covers for Solid Waste Landfills.
[4] G. B. Sowers and G. F. Sowers, Introductory Soil Mechanics and Foundations (Macmillan Company, 1970).



NOTE: UNIT WEIGHT OF WATER, γ_W = 62.4 LB/FT.

WATER CONTENT $w = \frac{W_w}{W_s}$

$\theta = \frac{V_w}{V}$

DRY UNIT WEIGHT (DRY DENSITY) $\gamma d = \frac{W_s}{V}$

VOID RATIO $e = \frac{V_v}{V_s}$

POROSITY $n = \frac{V_v}{V} = \frac{e}{1+e}$

DEGREE OF SATURATION $s = \frac{V_w}{V_v}$

Figure 1. Fundamental relationships in soil. (From R. J. Lutton, G. L. Regan and L. W. Jones, Design and Construction of Covers for Solid Waste Landfills, EPA 600/2-79-165 [EPA, 1979].)

Table 6

Atterberg Limits*

Stage	Description	Boundary or Limit
Liquid	A slurry; pea soup to soft butter; a viscous liquid	Liquid limit (LL)
Plastic	Soft butter to stiff putty; deforms but will not crack	Plastic limit (PL)
Semisolid	Cheese; deforms permanently but cracks	Shrinkage limit (SL)
Solid	Hard candy; fails completely upon deformation	

*Source: G. B. Sowers and G. F. Sowers.

Soil compressibility is directly proportional to the liquid limit (LL). The range in water contents through which the soil is considered to be in a plastic state is termed the plasticity index (the difference between liquid and plastic limits). The ratio of the plasticity index (PI) to the percentage of clay sizes (finer than 0.002 mm) is known as the activity (A). Activity is a measure of the clay minerals' water-holding ability and is used to indicate whether a clay is a kaolinite (low activity, $A<1$), a montmorillonite (high activity, $A>4$), or illite (intermediate activity, $1<A<2$).

Mechanical compaction can alter soil properties that have major importance for a soil cover or liner. When considering liners and, in most cases, covers, the most important effect of compaction is on soil permeability. Design parameters for compaction are based on a unique density value (maximum density) and a corresponding moisture content (optimum moisture content). Generally, it can be assumed that the more granular (sandy) the soil, the higher the maximum density and the lower the optimum moisture content. Also, the finer (the more clayey) the soil, the less defined the maximum density is as a function of the moisture content. Soils typically used as liners or covers have a clay content greater than 25 to 30 percent with poorly defined maximum density. Thus, density quality control in the field requires attention and skill.

Field testing should not end with single sample density testing. The choice of procedures for field compaction should be based on test results and general information about the site and soils involved. Information that must be quantified with the test results includes any increase in compactive energy or in persistence of the applied energy, or any decrease in layer thickness, all of which produce denser soil.

In highly plastic, clayey soils with high moisture contents, the use of heavy rollers to achieve the required compaction can lead to over compaction. Positive pore pressures develop in the clay when pressure cannot dissipate due to the clay's low permeability. To minimize overcompaction, a procedure called "stage compaction"* is recommended. The main reason for using stage compaction is that most of the compactive effort is used in densification, which should yield a soil blanket with lower permeability. In general, when compacting highly plastic, clayey soils or when the moisture content is above optimum, stage compaction should be used with an increased number of passes over the compacting layer.

In all cases, especially when the area is covered by different soil types, the design specifications should define the desired compaction as a "percentage of the laboratory maximum density."[5] In addition, the problem of compacting cover material on refuse should be considered, because large pieces of refuse such as metal or wood objects can penetrate a soil liner or cover

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*Stage compaction is the "principle of matching the supporting value and compactibility of soil layers by appropriate compacting effort, height, and efficiency of roller for two or more stages of compaction in order to insure efficiency and effectiveness of compaction at all stages." D. M. Burmister, 1964, ASTM Symposium, Compaction of Soils, ASTM STP 377, pp 47-66.

[5] H. Haxo, Lining of Waste Impoundment and Disposal Facilities, EPA 530/SW-870c (EPA, Office of Water and Waste Management, 1980).

after compaction. Moreover, the relatively soft base of the refuse can make it difficult to obtain proper cover compaction.

Soil permeability can be lowered by reducing the void ratio through compaction. Changes take place in the soil to impede the flow of water when the void ratio is reduced. Thus, the effective volume available for flow and the median pore size decrease. In nature, most soils with more than 25 to 30 percent clay-sized particles have undisturbed soil permeabilities in the range of 10^{-7} to 10^{-5} cm/sec. For soils with permeabilities in this lower range, many factors other than particle size affect permeability; these factors include the type of clay minerals present, the particle size distribution in the <2 μm fraction, and the effects of hydration and remolding on the soil. Montmorillonite clays' permeabilities, for example, are extremely sensitive to such physicochemical factors.

A clay soil's permeability is higher when compacted on the dry side of the optimum moisture content than when compacted on to the wet side. When compacted "dry of optimum," the clay has an open, flocculated structure, whereas clay compacted on the wet side has a dispersed structure (see Figure 2).[6] Also, "dry-of-optimum" clay tends to reproduce the structure of a "wet" clay. Laboratory soil specimens compacted at very high moisture contents have had their permeabilities lowered by structural arrangement of the soil rather than by reducing the total void space.[7]

The soil's type of formation and natural preconsolidation pressure will determine its remolding characteristics and resulting permeability for use as a liner or cover. Texas and New Orleans clays that have been sedimented in fresh waters and highly precompressed cannot be remolded efficiently. However, soils such as the Scandinavian sensitive clays, which have been precompressed by nature at very low stresses, can be remolded quite efficiently.[8] To produce soils with the lowest possible permeability, the following should be considered:

- Lowest permeabilities result when the soil is compacted at a wet-of-optimum moisture content.

- Soil density becomes more critical when compaction is done at higher moisture contents (a 1 percent decrease in density can increase permeability one order of magnitude).

- Compactive efforts using shear deformation can result in a lower permeability.

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[6] T. W. Lambe, "The Structure of Compacted Clay," J. Soil Mech. Found. Div., Vol 84, No. SM2 (1958), p 34.

[7] J. K. Mitchell, D. R. Hooper, and R. G. Campanella, "Permeability of Compacted Clay," J. Soil Mech. Found. Div., Vol 91, No. SM4 (1965), pp 41-65.

[8] J. K. Mitchell, "The Fabric of Natural Clays and Its Relation to Engineering Properties," Proc. Highway Res. Bd., Vol 35 (1956), pp 693-713.

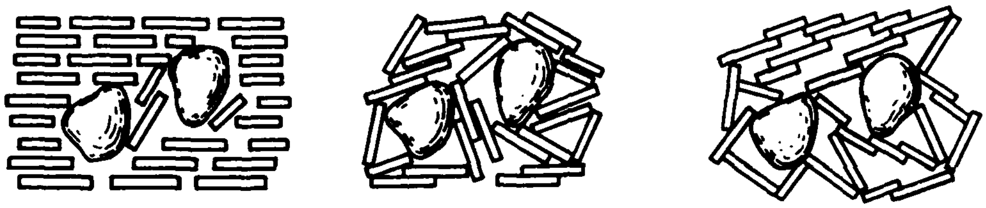

Figure 2. Cohesive soil structures. (From T. W. Lambee, "The Structure of Compacted Clay," Amer. Soc. Civil Eng. J. Soil Mech. Found. Div. Vol 84, No. S72 (1958), p 34.

• The sensitivity of a clayey soil should be determined by measuring the decrease in permeability as a function of increasing moisture and compactive effort.

• Testing the soil under accurately reproduced field conditions is very important in determining liner/cover permeability.

Chemical Compatibility of Natural Materials

Clay is a good liner material that is relatively inert to chemical attack; it will also act as a filter, absorbing many contaminants from the leachate.[9] However, the relative chemical compatibility of clay soils with landfill leachate is based on very limited data and experience at the present time.

When using natural liners and covers, soil permeability is the most important property a waste leachate can alter. The most relevant properties affecting soil permeabilities are:

• The soil's dispersing/flocculating properties when in contact with leachate

[9] M. Kelley, Assessment of Technology for Constructing and Installing Cover and Bottom Liner Systems for Hazardous Waste Facilities, Interview Report (U.S. Army Engineer Waterways Experiment Station, December 1982).

• The soil's shrink/swell properties when in contact with leachate

• The change in the soil's pore-size distribution after contacting waste leachate

• The dissolution/precipitation of chemicals, which can alter the proportion of soil volume available for flow

• How the soil's adsorption properties change.

Different organic fluids affect soils in various ways. Organic acids are potentially very reactive with and mobile in clay liners, possibly causing dissolution and piping failure. Organic bases are cationic and thus adsorb very strongly to clay surfaces; this causes volume changes by altering the interlayer spacing. Neutral nonpolar organics can move through clay soils, rapidly eroding and enlarging the pores through which they pass. These same chemicals can also increase permeabilities by displacing water from the clay which may, in turn, cause shrinkage of the clay structure. Neutral polar organics can affect permeability by changing (1) the interlayer spacing in the clay and (2) the pore water's surface tension which in turn affects the shrink-swell and flow properties of the clay. Since water properties can change drastically when dissolved chemicals are present, a clay used as a liner or cover can shrink, swell, heave, crack, or pipe. Water can also increase the hydraulic gradient that moves fluids through soil increasing the permeability.

Anaerobic decomposition in the landfill is a persistent source of organic acids that can solubilize parts of a clay liner. Inorganic acids and bases can also have this effect. Acids are known to dissolve aluminum, iron, alkali metals, and alkaline earths whereas bases dissolve silica. Clay contains large amounts of both aluminum and silica, making it particularly susceptible to partial dissolution by these acids and bases.

Testing of clay's compatibility with different organic and inorganic fluids has indicated the need for more laboratory testing and for field work to determine the validity of generalizations from previous laboratory studies.[10] Until the effects of various waste leachates on clay soil liners are known, landfill designers should insure that clays to be used at a given site are subjected to detailed permeability and shrink-swell testing with mixtures of the waste leachate that will typically be produced in the landfill.[11] As a preliminary step to compaction and shrink-swell testing with a waste leachate, two sets of tests should be performed with distilled water and a 0.01 N calcium sulfate solution. If there is a drastic change in the permeability of the clay when exposed to the water and the calcium sulfate

[10] W. J. Green, G. F. Lee, and R. A. Jones, Impact of Organic Solvents on the Integrity of Clay Liners and Industrial Waste Disposal Pits: Implications for Groundwater Contamination, Project Report R-804-549-010-02-0 (R.S. Kerr Laboratories, June 1979).

[11] W. J. Green, G. F. Lee, R. A. Jones, and T. Pallt, "Interaction of Clay Soils With Water and Organic Solvents: Implications for the Disposal of Hazardous Wastes," Environ. Sci. Technol., Vol 17 (1983), pp 278-282.

solution, a waste leachate should be used to determine the Atterberg limits of the clay.

Installation of Soil Liners and Covers

The procedures for constructing covers and liners are similar; the goal is to compact and remold in-place or imported soil into a layer that restricts the flow of liquids. Such a layer is needed in a cover to restrict surface water from percolating into the waste material. In a liner, this impermeable layer impedes waste fluid flow from the landfill into the groundwater or vice versa.

The construction of soil liners and covers should be guided by specifications that incorporate enough flexibility to account for soil and construction variability. These specifications should describe the performance required from the liner or cover and should detail the procedures needed to achieve that performance.

For example, procedural specifications for soil (clay) liners and covers should include:

- Liner or cover thickness
- Thickness of each layer to be compacted at once
- Weight and type of compacting equipment
- Number of passes required by the compacting equipment over each layer
- Moisture content of the material to be emplaced required to produce the specified density.

An important feature of construction is inspection of the work performed. This must be done by visual observation and testing. Inspections should be made during construction in cooperation with the contractor. This allows contractors to see the results and improve their operation tc provide work that meets specifications.

Liners

When constructing a soil liner, all vegetation must be removed, especially tree trunks and roots. Any depressions that result should be backfilled with clean soil before proceeding with the liner. Surface water collecting from rain or from digging into groundwater can cause problems with liner installation; it can hinder the movement and operation of heavy equipment, making it difficult to achieve the proper liner density and moisture relationship. When groundwater persists and grading to divert it is not possible, an artificial base or underdrain system should be constructed. One way to do this is by packing various-sized gravels into the earth and covering it with sand or similar material to achieve a stable, firm surface for the liner.

When designing and constructing slopes, the soil should be compacted to densities and moisture contents that will generate the least permeable soil.

Consideration should be given to the strength of the compacted soil only if a critically weak soil results. In that case, procedures should be investigated to develop the most economical way of improving the soil's strength with the least effect on liner permeability.

Side slopes should be constructed by standard techniques. Most compaction equipment can operate successfully on slopes up to 3:1 under normal conditions. During wet periods, the compaction equipment can be linked to other heavy equipment or to a winch stationed at the top of the berm or sidewall. The equipment at the top is used to pull the compactor up the slope and slow its downslope run. Side slopes steeper than 2:1 can be compacted using two similar pieces of equipment chained together. One machine crosses the flattened top of the slope while the second works the slant.

Covers

Standard techniques apply when constructing the final landfill cap. The buffer layer between the refuse and barrier should have enough thickness and density to provide a smooth, stable base for the barrier layer. All layers should be compacted except for the final topsoil. The barrier layer should be compacted to 90 percent of the maximum density according to ASTM D 1556 or other suitable standard. This layer should be covered immediately after compaction to prevent drying and cracking. The barrier layer should also be thick enough to prevent formation of excessively thin spots during spreading. Construction should be in units small enough to allow completion and covering each day. If possible, the final topsoil layer should be seeded at the time of spreading; it should be mulched to prevent erosion and to retain enough moisture for plant growth.

Mechanical Failure

The most common and significant type of mechanical failure during installation or operation results from differential settling of the soil or refuse. This type of failure is more common with covers since the refuse underneath typically has pronounced differential settlement. Relatively little is known about designing soil liners and covers for subsidence.

5 SYNTHETIC MEMBRANES AS LINERS AND COVERS

Characteristics of Synthetic Materials

Synthetic membrane technology is new, with a wide variety of synthetic materials and compounds being manufactured, tested, and marketed. These membranes vary in physical and chemical properties (including compatibility with leachate), as well as in installation procedures and costs. There is also considerable variation in membrane compounding and manufacturing among producers. The finished synthetic membrane consists of raw polymer combined with ingredients such as carbon black, pigments, fillers, plasticizers, processing aids, crosslinking chemicals, antidegradants, and biocides. Table 7 lists the polymer producers by tradename or common identification and the respective suppliers of the finished materials.

The polymer compound is mixed and then converted into rolls of sheeting 1.22 to 2.44 m wide and hundreds of meters long. This sheeting is seamed together into panels as large as 31 m by 62 m, depending on weight and handling limitations. Seaming techniques include the use of heat, dielectric currents, adhesives, and solvent welding. For field seaming, the manufacturer should specify the seaming technique to be used, including quality control procedures. In general, factory seams are more reliable than field-generated seams because they are formed under more controlled conditions. Air lancing and ultrasonic methods can be used to inspect the finished, in-place membrane.

Four types of polymers are generally considered for use in membranes:

- Rubbers (elastomers), usually vulcanized
- Plastics, usually unvulcanized, such as polyvinyl chloride (PVC)
- Plastics with high crystalline content, such as polyolefins
- Thermoplastic elastomers that do not need vulcanizing.

Table 8 lists the various types of polymers used. The polymeric materials most frequently used in liners and covers are PVC, chlorosulfonated polyethylene (CSPE), chlorinated polyethylene (CPE), butyl rubber, ethylene propylene rubber (EPDM), neoprene, high-density polyethylene (HDPE), and low-density polyethylene (LPDE). The thickness of polymeric membranes used in landfills ranges from 20 to 120 mils (0.5 to 3 mm) with most in the 20- to 60-mil (0.5- to 1.5-mm) range. Most materials are based on one polymer; however, various blends or rubber-plastic alloys are being developed that will have considerably improved strength and chemical compatibility. Most membrane liners and covers are manufactured from polymeric compounds that are unvulcanized or uncrosslinked and therefore thermoplastic. The material's thermoplasticity allows it to be heated for fusing or seaming and still retain its original properties when cooled. The thermoplasticity of an unvulcanized material allows for a more reliable seam compared to the same vulcanized material. This explains why materials such as CPE or CSPE are used in an unvulcanized form even though the vulcanized form is more chemically resistant.

Table 7

Polymer Producers and Suppliers*

Polymer	Trade Name	Company
Butyl rubber		Exxon Columbian Carbon Polysar
Chlorinated polyethylene	CPE**	Dow Chemical
Chlorosulfonated polyethylene	Hypalon	Du Pont
Elasticized polyolefin	3111	Du Pont
Epichlorohydrin rubbers	Herclor Hydrin	Hercules B.F. Goodrich
Ethylene propylene rubber	Epcar Epsyn Nordel Royalene Vistalon	B.F. Goodrich Copolymer Du Pont Uniroyal Exxon
Fluorocarbon polymers	Viton/Teflon	Du Pont
Neoprene (chloroprene rubber)	Neoprene**	Du Pont Denka
Nitrile Rubber	Chemigum Hycar Krynac NYsyn Paracril	Goodyear B.F. Goodrich Polysar Copolymer Uniroyal
Polybutylene	-	Shell Chemical
Polyester	Hytrel	Du Pont
Polyethylene - HDPE - LDPE	- -	Many Many
Polyvinyl chloride	PVC**	Borden General Tire B.F. Goodrich Firestone Pantasote Stauffer Tenneco Union Carbide
Thermoplastic elastomer	Santoprene TPR	Monsanto Uniroyal
Urethane	-	Many

*Source: H. Haxo, Lining of Waste Impoundment and Disposal Facilities.
**Generic name.

Table 8

Polymeric Materials Used in Liners and Covers*

Polymer	Thermo-plastic	Vulcanized	Fabric Reinforcement With	Fabric Reinforcement W/O
Butyl rubber	No	Yes	Yes	Yes
Chlorinated polyethylene	Yes	Yes	Yes	Yes
Chlorosulfonated polyethylene	Yes	Yes	Yes	Yes
Elasticized polyolefin	Yes	-	No	Yes
Elasticized polyvinyl chloride	Yes	-	Yes	No
Epichlorohydrin rubber	Yes	Yes	Yes	Yes
Ethylene propylene rubber	Yes	Yes	Yes	Yes
Neoprene (chloroprene rubber)	No	Yes	Yes	Yes
Nitrile rubber	Yes	-	Yes	-
Polyethylene	Yes	No	No	Yes
Polyvinyl chloride	Yes	No	Yes	No

*Source: H. Haxo, Lining of Waste Impoundment and Disposal Facilities.

Butyl Rubber

Butyl rubber liners have been used for over 30 years in potable water impoundments. Butyl rubber is a copolymer, made of isobutylene (97 percent) and isoprene to allow for vulcanization. It has:

- Low gas and water vapor permeability
- Thermal stability
- Ozone and weathering resistance
- Chemical and moisture resistance
- Resistance to animal and vegetable fats and oils.

It also has a high tolerance for temperature extremes and retains flexibility throughout the service life. However, butyl rubber is very difficult to repair and seam because it requires special vulcanizing adhesives that are useful only under controlled temperatures.

Chlorinated Polyethylene (CPE)

This material is produced by a chemical reaction between chlorine and high-density polyethylene. CPE is compounded and used in both thermoplastic and vulcanized polymers. It has:

- Resistance to ozone and weathering
- Good tensile and elongation strength
- Resistance to many corrosive and toxic chemicals
- Resistance to the growth of mold, mildew, fungus, and bacteria.

Aromatic hydrocarbons and oils cause CPE to swell, and continuous exposure can shorten the service life. CPE can be compounded with other polymers to improve stress-crack resistance and softness of ethylene polymers and to improve the cold-crack resistance of flexible PVC. CPE membranes usually are not vulcanized and can therefore be seamed by solvent adhesives, solvent welding, or dielectric heat sealing.

Chlorosulfonated Polyethylene (CSPE)

This material is made by reacting polyethylene in solution with chlorine and sulfur dioxide. CSPE is used in both thermoplastic and vulcanized compositions. It has:

- Resistance to ozone, heat, and weathering
- Resistance to corrosive chemicals (acids and alkalines)
- Resistance to the growth of mold, mildew, fungus, and bacteria.

CSPE is usually reinforced with polyester or nylon scrim, which gives needed tear strength for use on slopes and reduces distortion resulting from shrinkage when placed on the base and when exposed to the sun's heat. Thermoplastic CSPE can be seamed using heat, dielectric heat, solvent welding, or solvent adhesives. The disadvantages of CSPE are poor resistance to oils, shrinkage when exposed to sunlight, low tensile strength, and a tendency to harden with aging.

Elasticized Polyolefins

This material is a blend of rubbery and crystalline polyolefins. Elasticized polyolefins are unvulcanized, thermoplastic material that is easily heat sealed in the field or factory. It has:

- Resistance to weathering, alkalines, and acids
- Low density (0.92).

This material generally is produced in sheets 20 mils (0.5 mm) thick, 6.2 m wide, and up to 62 m long. It is difficult to handle at low temperatures and high winds and is not resistant to oils.

Epichlorohydrin Rubbers

This classification includes two types of homopolymer and a copolymer of epichlorohydrin and ethylene oxide. These materials are vulcanized with a variety of reagents, including diamines, urea, and ammonium salts. They have:

- Resistance to hydrocarbon solvents, fuels, and oils
- Resistance to ozone and weathering
- Low rate of gas/vapor permeability
- Good low and high range thermal stability (0 to 300°F [-17.7 to 148.2°C])
- Good tensile and tear strength.

These materials can be seamed at room temperature with vulcanizing adhesives.

Ethylene Propylene Rubber (EDPM)

This material is produced with ethylene, propylene, and small amounts of nonconjugated diene hydrocarbon. EPDM is usually vulcanized with sulfur; however, thermoplastic EPDM is also available. These materials have:

- Resistance to weathering, ozone, and ultraviolet radiation
- Resistance to abrasion and tear
- Resistance to temperature extremes
- Resistance to dilute solutions (10 percent by weight) of acids, alkalis, silicates, phosphates, and brine.

Vulcanized EPDM can be seamed with special cements; however, the seaming technique should be tested in the service environment. This material is not resistant to petroleum, aromatic, or halogenated solvents.

Neoprene

This material is a synthetic rubber based on chloroprene. Neoprene is vulcanized with metal oxides or sulfur and has:

- Mechanical properties similar to natural rubber
- Resistance to oils, weathering, ozone, and ultraviolet radiation
- Resistance to puncture, abrasion, and mechanical damage.

Vulcanizing cements and adhesives are used for seaming.

Polyethylene

This material is produced in low-density (LDPE) and high-density (HDPE) types. Polyethylenes are used in thermoplastic form and have:

- Very good resistance to oils and solvents (HDPE)
- Resistance to permeation by water vapor and gases
- Resistance to ultraviolet degradation when 2 to 3 percent carbon black has been added.

LDPE is produced in thin sheets, which makes it difficult to handle and field seam; it is easily punctured under impact. HDPE is produced in sheets as thick as 272 mils (6.8 mm).

Polyvinyl Chloride (PVC)

This material is a thermoplastic polymer compounded with plasticizers and other modifiers to produce a wide range of physical properties. PVC is produced in roll form in many widths and thicknesses. It has:

- Good chemical resistance to many inorganic chemicals
- Resistance to elongation, puncture, and abrasion
- Resistance to microbiological attacks when compounded with a biocide.

The sun's heat can cause loss of the plasticizer by volatilization. Carbon black prevents ultraviolet degradation but absorbs solar energy, which raises the temperature enough to vaporize the plasticizer. For these reasons, PVC is not recommended for areas with exposure to ultraviolet light or weather. When specialty plasticizers are used, oil-resistant grades of PVC can be produced. Polymers such as nitrile rubber, CPE, and EVA are used to replace the liquid plasticizers so that blended PVC is more resistant to certain waste fluids.[12] For these reasons, PVC membranes have become the most widely used polymers for waste impoundments.

Thermoplastic Elastomers (TPE)

This material is a relatively new, varied class of rubbery polymeric compositions. TPEs are used in thermoplastic, nonvulcanized form and behave much like vulcanized rubber, with:

- Resistance to ozone and weathering
- Resistance to oil, fuel, and water
- High tensile strength.

[12] Haxo, H., Lining of Waste Impoundment and Disposal Facilities.

As with other thermoplastic polymers, TPE can be seamed by heat techniques. Materials such as thermoplastic EPDM and nitrile rubber/PVC blends are still being tested to determine their durability in different chemical environments.

Chemical Compatibility of Synthetic Materials

Most polymeric materials tend to swell when exposed to fluids. Swelling usually has adverse effects on polymeric materials, such as:

- Softening
- Loss of tensile and mechanical strength and elongation
- Increased permeability and potential for creep
- Increased susceptibility to polymer degradation.

For these reasons swelling has been used to indicate membrane compatibility with waste fluids. The swelling ability of polymer or rubber membranes can be reduced by crosslinking or vulcanized.

Data are very limited on the field effects of waste leachates on membrane liners and covers. Information on polymer membrane compatibility with different waste fluids is based on laboratory and bench-scale simulations, but even this type of data is limited. Landfill simulator studies have been performed with different polymers to compare the membrane swelling characteristics in water and leachate.[13] Results have shown that membrane swelling is higher in leachate than in water, probably due to the organic constituents in leachate. The results of immersing several polymers in leachate and water are presented in Table 9.[14] The effects of leachate absorption on tensile strength were also studied in these simulations, with results indicating that tensile strength decreased with increasing leachate absorption. The loss in tensile strength is attributed to the swelling and the resulting reduced amount of polymer in the material's cross section.

Limited data are available on exposure of membranes to hazardous wastes. One study exposing different membranes to various hazardous wastes for over 3 years indicated the following general trends:

- CSPE, neoprene, and EPDM lost significant elongation in caustic, lead, and nitric acid wastes, respectively
- Polyester elastomer completely lost its elongation in a strong acidic waste
- CSPE and PVC stiffened during exposure to acid, alkali, oil, lead, and pesticide wastes

[13] Haxo, H. E., "Compatibility of Liners with Leachate," Management of Gas and and Leachate in Landfills: Proceedings of the Third Annual Municipal Solid Waste Research Symposium, EPA-600/9-77-026 (EPA, 1977).
[14] Haxo, H. E., "Compatibility of Liners with Leachate."

Table 9

Water and Leachate Absorption by Polymeric Liners*
(Percent Absorbed by Weight)

	Liner No.	Water (1 yr)	Leachate (1 yr)
Butyl rubber	7[a]	1.60	1.78
	22	1.70	2.32
	24	1.10	1.0
Chlorinated polyethylene	12[b]	13.10	9.0
	13[b]	19.60	12.4
	23	15.50	10.3
Chlorosulfonated polyethylene	3	17.40	20.0
	4[b]	18.00	19.0
	6[a,b]	9.20	13.64
	14[b]	11.20	8.71
Ethylene propylene rubber	8	1.40	5.95
	16[a]	4.80	5.50
	18	...	...
	25	1.50	5.99
	26	1.60	8.99
Neoprene	9	22.7	8.73
Polybutylene	20	0.25	0.33
Polyethylene	21[b]	0.20	0.25
Polypropylene	27	0.28	0.40
Polyvinyl chloride	10	1.85	6.72
	11	1.85	5.0
	15	2.10	4.64
	17[b]	1.85	3.29
	19	0.60	0.75

*Source: H. Haxo, Lining of Waste Impoundment and Disposal Facilities.
[a]Liners mounted in generator bases.
[b]Fabric-supported liner.

- Neoprene softened when exposed to the same wastes

- Immersion in oil wastes caused a large swelling in CPE and CSPE.[15]

Special one-surface exposure tests called "pouch tests" have also been completed.[16] Figure 3 is a schematic of a pouch test in which the waste fluid was placed in a small pouch (made from the membrane) and immersed in deionized water. By measuring the change in pouch weight and the water's pH and electrical conductivity, membrane permeability to the waste fluid and water was determined. The bag's weight increased over time because of water entering by osmosis. Table 10 gives the increase in pouch weight for three different wastes. Table 11 indicates the material's relative permeability by estimating the time required for ionic material to diffuse through the pouch into the water and raise its conductivity to 1000 mho. The data show that PVC has greater permeability compared to other membranes. A similar pouch test was run with a 5 percent sodium chloride solution (Table 12). Again, the PVC material had greater permeability.[17]

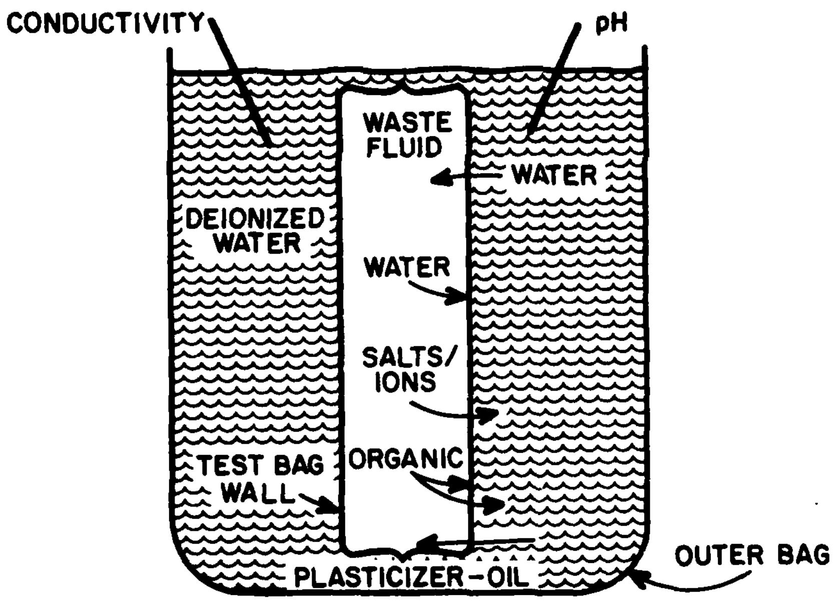

Figure 3. Schematic of pouch test for membrane liner materials. (From H. Haxo, Lining of Waste Impoundment and Disposal Facilities.

[15]Haxo, H. E., "Interaction of Selected Liner Materials With Various Hazardous Waste," Disposal of Hazardous Wastes, Proceedings of the Sixth Annual Research Symposium, EPA-600/9-80-010 (EPA, 1980).

[16]Haxo, H. E., Lining of Waste Impoundment and Disposal Facilities.

[17]Haxo, H. E., Lining of Waste Impoundment and Disposal Facilities.

Table 10

Relative Permeabilities of Polymeric Membrane Lining Materials in Pouch Test With Three Wastes*

Polymer[a]	Liner No.[b]	Nominal Thickness (mils)	Average Flux into Pouch ($gm/m^2/day \times 10^{-2}$) HNO$_3$ Waste	Spent Caustic	Slopwater
Chlorinated polyethylene	86	22	78.2	26.3	190.7[c]
Chlorosulfonated polyethylene	85	33	67.8	36.3	49.2
Elasticized polyolefin	36	23	2.5	3.8	18.4[d]
Polybutylene	98	7.5	3.0	7.9	13.6
Polyvinylchloride	19	22	32.4	78.8	325.0
Polyvinylchloride	88	20	64.2	65.9	118.89

*Source: H. Haxo, Lining of Waste Impoundment and Disposal Facilities.
[a]Exposure time is 552 days unless otherwise noted.
[b]Matrecon identification number.
[c]Pouch failed at 450 days.
[d]Pouch failed at 300 days.

Table 11

Permeability of Thermoplastic Polymeric Materials in Osmotic Pouch Test*

Polymer	Liner No.[a]	Wall of Inner Bag: Thickness (mils)	Extractables (%)	Waste in Inner Bag: NHO$_3$ Waste	Slopwater
Chlorinated polyethylene	86	20	--	200	420
Chlorosulfonated polyethylene	85	33	--	500	510
Elasticized polyolefin	36	22	5.5	300	1000
Polybutylene	98	7	--	600	1000
Polyvinylchloride	19	20	38.9	70	200
Polyvinylchloride	88	20	33.9	110	160

*Source: H. Haxo, Lining of Waste Impoundment and Disposal Facilities.
[a]Matrecon identification number.

Table 12

Pouch Test of Thermoplastic Membranes*

Polymer	Chlorosulfonated polyethylene	Elasticized polyolefin	Polyvinyl chloride
Liner No.**	6	36	59
Thickness (mils)	32	23	33
Volatiles content of exposed pouch walls (%)	8.7	0.38	0.90
Changes in weight of pouch plus waste (%)	+2.6	+0.71	+0.38
Change in weight of fluid in pouch during exposure (%)	+0.95	+0.76	+0.38
Conductivity of water in outer pouch (mho)	585	34	4500
Retention of physical properties (%)			
Elongation	95	100	94
S-100	106	119	120

*Pouches were filled with 5 percent NaCl solution and exposure time was 1150 days (164 weeks). Source: H. Haxo, Lining of Waste Impoundment and Disposal Facilities.

**Matrecon identification number.

Installation of Synthetic Membranes

One of the most important components of installing a synthetic liner or cover membrane is subgrade preparation. Since the subgrade supports the membrane, its quality and integrity must be insured or the unsupported membrane could fail. The subgrade below a liner would have to support a much greater load than would that below a cover; however, the subgrade is critical for both liners and covers and good construction practices apply to both.

During the planning stages of a landfill, the natural soils should be analyzed and tested for physical, mechanical, and chemical characteristics. These tests should determine, among other things, the soil's shrink/swell properties and the subgrade soil's density, strength, settlement, and permeability. The soil's clay mineralogy, ion exchange capacity, solubility, and organic content can also be important. Soils with high shrink/swell tendency can weaken earthen structures and cause membrane failure. Void spaces can also develop as a result of shrink/swell cycles, which can cause liner or cover failure.

Organic material in the subgrade can cause failure in several ways: decaying tree trunks or roots can leave void spaces in the subgrade, causing membranes to stretch and tear, and the decaying process can generate gases that can collect beneath a membrane and cause ballooning, which leads to local distortion and rupture. Soluble material in the subgrade can also cause gas and void problems. For example, if an acid reaches a carbonate-rich soil, gas is produced and voids are created by dissolution of the carbonate. Similar problems can occur with a highly fluctuating water table. When the water table falls, voids develop and draw in air from surrounding soil. When the water table rises again, this air is forced upward and can be trapped under the membrane. The amount of fluctuation dictates the "air pumping" action and the resulting effect on the membrane.

Organic material should always be removed during subgrade preparation and the resulting depressions should be filled with sand or clean soil. Other gas problems can be solved by sloping the subgrade 2 to 4 percent upward from the middle of the fill zone. A pathway for gas movement can then be made by installing a layer of clean sand (less than 5 percent passing the 200 sieve) below the membrane. Gas vents should be installed on the inside slope of the berm, approximately 30 cm down from the crown of the dike.

The subgrade should provide firm, smooth, unyielding support for the membrane. The largest particles in the subgrade soil should be less than 2 cm and should be rounded, not angular to prevent puncturing the liner. Large gravel or similar material should be removed to a depth of 7.6 to 15.2 cm below the desired fill bottom elevation; it should be replaced with proper backfill to provide the needed smooth support for the membrane. The material used for the impoundment should be stable under differing loads and climates. Generally, side slopes of 3:1 or lesser slope are safe for most soils. Weaker soils or seismic conditions may dictate gentler slopes to prevent failure under the membrane. The most efficient impoundment design is rectangular with straight sloping sides. Curved sides, irregular shapes, or circular landfills greatly increase grading and installation costs as well as the number of seams and possible failure points.

Whether a subgrade is built in a series of compacted layers (as in a fill subgrade) or is compacted only once at its surface (as in an excavated subgrade), the minimum compaction needed should be specified in one of two ways: (1) by requiring the in-place subgrade density to achieve a specified percentage of that obtainable by the Standard Proctor Test, ASTM D698, or (2) by writing specifications giving the required compaction equipment, number of passes per layer, layer thickness, and allowable moisture content.

After compaction, the surface is fine-finished by having work teams scour the surface of the base and sidewalls to remove all visible rocks, debris, and vegetation. The vegetation must be removed because some grasses can actually penetrate membranes. If woody vegetation or grasses such as salt grass, nut grass,or quackgrass are present, the topsoil layer should be removed and a soil sterilizer should be applied before liner placement. Time must be allowed for the sterilizer to be absorbed by the subgrade or lose its volatile components so those chemicals will not react with the membrane. When selecting vegetation to be placed on the final cover, only short-rooted varieties should be considered to avoid deep roots that can penetrate the membrane cover. After removal of debris, the teams should fill in all depressions or other irregularities with sand. Vibrating rollers and drag plates can be used on slightly wet surfaces to obtain the smoothest possible surface. The liner should be placed as soon as possible after fine finishing to avoid erosion that could result from a rainstorm.

Surface and subsurface drainage can adversely affect covers and liners. Thus, in areas with high and/or fluctuating water tables or those subject to flooding, underdrain systems may be needed to remove water from beneath the liner. In addition, surface diversion systems may be needed to prevent damage to membrane covers.

Geotextiles are sometimes used to prevent subsurface drainage systems from clogging. These drainage systems may be placed either above or below a liner, depending on the application. A geotextile may also be used to provide additional structural integrity to a synthetic membrane. Placed below a membrane, it protects the liner against punctures from angular pieces of gravel, or it may be placed above a liner to protect it against punctures by the buried waste, or against damage from machinery used to spread a cover layer.

Temperature can affect the membrane's installation procedure as well as its service life. Temperature extremes expected while the membrane is in service should be determined to select the proper membrane material. Most synthetic membranes can successfully handle typical sanitary landfill temperatures. Temperatures during installation can affect membrane placement and seaming: low temperatures can make a membrane brittle and difficult to handle, whereas high temperatures can cause a membrane to be too stretchy.

Inflow/outflow piping such as monitoring wells, gas vents, leachate drainage, or recyclers should be designed for "over the top" if possible. The fewer penetrations through the cover, the better it will perform. Piping should be compatible with the membranes to allow for good sealing when penetrations are necessary. The subgrade around pipes should be well compacted to insure against void spaces.

Actual placement of the membrane liner or cover requires careful planning. This plan should consider storage and security of the membrane and all related equipment, manpower requirements, field seaming, anchoring, inspection, and protection for the in-place membrane. Most membranes are packaged in folded panels or rolls weighing as much as 900 to 2250 kg each. If possible, these should be stored out of sunlight to prevent degradation and blocking (the sticking together of membrane material) which, upon unfolding, can cause delamination or ripping.

Equipment needed to install the membrane depends on the material and seaming technique used. Materials such as HDPE require specialized equipment to weld the seams. In cold climates, a heat gun might be needed to preheat membrane seams before the welding equipment will work properly. Materials that require rollers for field seaming should be seamed using a board (2.5 cm by 30 cm by 3.7 m) under the membrane to provide support. With an attached rope, this board is pulled along under the membrane from the middle of the panel toward the edges as the seam progresses. Panels can be held in place with old tires or sandbags during seaming. These sandbags or tires also prevent wind damage to the material (see Figure 4).

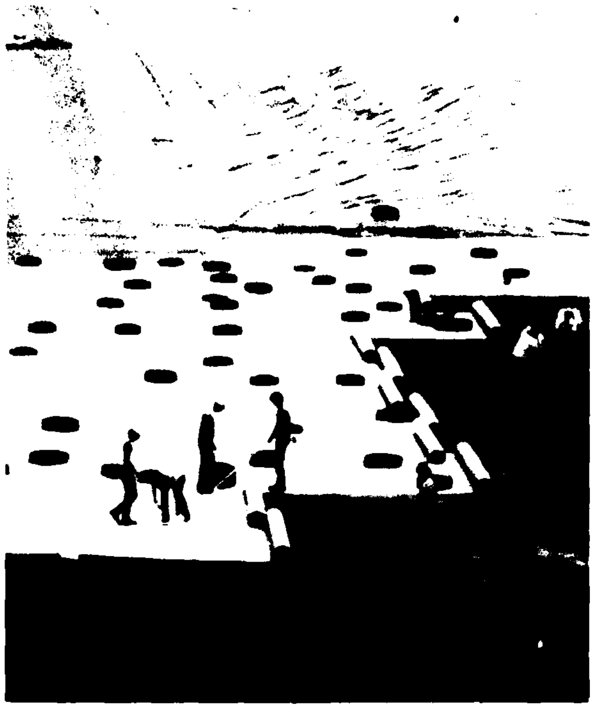

Figure 4. Tires hold panels in place, preventing wind damage during seaming.

Many membrane materials require surface cleaning before seaming. Thus, a large supply of brushes, clean cotton rags, and stainless steel scouring pads may be needed, depending on the material. Some materials such as CSPE have a surface cure that must be removed before seaming. Safety equipment such as goggles, chemical-resistant gloves, and respirators should be used when working with solvents to clean the seams.

Knee pads, shoes with flat soles to prevent membrane damage, wax pencils to mark the seams, and other necessary equipment should be made available on site before membrane installation. In addition, wooden dowel rods should be provided to avoid stretching the membrane edges when large panels are moved across the subgrade. The edge of the panel is rolled up on the dowel rod to provide a handle for movement without stretching. Table 13 is a list of typical equipment needed when installing a membrane liner or cover.

Table 14 presents some basic considerations for actual membrane placement. Before placing or spotting the panels, the anchor trench around the impoundment's perimeter should be completed and the excavated dirt should be raked smooth. The subgrade should be smooth and compacted, there should be no standing water, and any inflow/outflow pipes or other structures requiring special treatment should be prepared before panel spotting. A liner membrane can be anchored in two ways: (1) by attaching it to a concrete structure, or (2) by using the trench-and-backfill method, which is simpler and more economical. Figure 5 illustrates the trench-and-backfill method, in which the liner is temporarily secured to the anchor trench during seaming. After a panel has been seamed, the trench is backfilled. This allows the panels to be aligned and stretched, if necessary, to obtain a wrinkle-free seam.

Table 13

Equipment and Materials for Installation of Flexible Membrane Liners*

Item	Use
Fork lift	To move liner panels and backfill anchor trenches
Tires, sandbags	To anchor unseamed panels and prevent wind damage
Proper adhesives	To make field seams and seal liner around concrete or steel penetrations
Portable electric generator	To operate heat guns or lighting for working at night
Air lance	To quality control test field seams
Hand-held earth tampers	To smooth subgrade as necessary
Miscellaneous materials	For field seaming
Adhesive applicators (paint brushes, calking guns, rollers, etc.)	
Liner preparation equipment (clean rags, scrub brushes, scouring pads, pails for solvent, hard surface rollers, seaming support board, heat guns, crayons for marking, dowels for pulling panels, stakes and chalk line, steel measuring tape, scissors and utility knives, electrical extension cords for heat guns)	
Field crew equipment	For field crew when making seams
Safety goggles, solvent-resistant gloves, knee pads, respirators, soft-soled shoes	
First aid kit	In case of accidents
Air compressor	To supply air that might be needed when working with solvents, and for air lance

Source: H. Haxo, Lining of Waste Impoundment and Disposal Facilities.

Table 14

Considerations for Liner Placement*

Follow manufacturer's recommended procedures for adhesive system, seam overlap, and sealing to concrete.

Use a qualified installation contractor who has experience with membrane liners, preferably the generic type of liner being installed.

Plan and implement a quality control program to help insure that the liner and the job meet specifications. Inspection should be documented for review and record keeping.

Install the liner during dry, moderately warm weather if possible.

Subgrade should be firm, flat, and free of sharp rocks or debris.

*Source: H. Haxo, Lining of Waste Impoundment and Disposal Facilities.

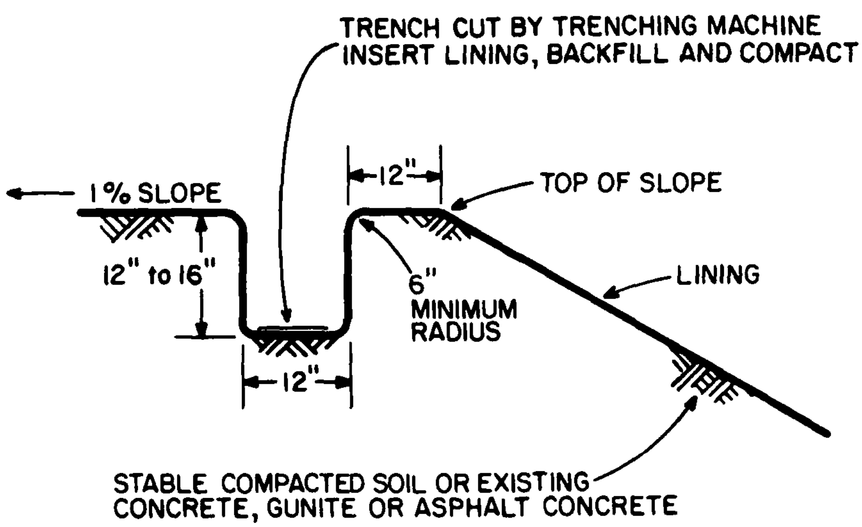

Figure 5. Schematic of anchor trench for membrane liner. (From H. E. Haxo, Lining of Waste Impoundment and Disposal Facilities.)

Field seaming is the most critical factor in membrane liner and cover installation. The membrane manufacturers should recommend sealing procedures and adhesives; if no bonding systems are recommended, the use of that specific membrane material should be questioned. Table 15 summarizes the seaming techniques available for various materials. The seam's integrity is determined mainly by the compatibility of (1) adhesive and liner and (2) the finished seam and the waste fluids it contacts.

Field seams are normally started at the center of the panel and worked toward each edge to eliminate wrinkles. Panels should be placed with seams running parallel to the long axis of the trench and always overlapped with the upslope panel on top of the downslope panel. This means that, as a general rule, field seams should run vertically on side slopes where possible without decreasing panel size or increasing the need for seams. Field seaming should not be done during rainstorms or high humidity and the number of panels spotted in one day should not exceed the number of panels seamed that day.

Table 15

Seaming Provisions for Synthetic Liners*

	Type of Compound**	Place Used	Solvents	Bodied Solvents	Solvent Cements	Contact Cements	Vulcanizing Adhesives	Tapes	Heat Sealed	Dielectric
Butyl rubber	XL	Factory	...	...	...	X	X	...	...	...
		Field	...	...	...	X	X	X	...	...
Chlorinated polyethy: .ne	TP	Factory	X	X	X	X	...	...	X	X
		Field	X	X	X	X	...	X	X	...
Chlorosulfonated polyethylene	TP	Factory	X	X	X	X	...	...	X	X
		Field	X	X	X	X	...	X	X	...
Elasticized polyolefin	TP	Factory	...	...	...	X	...	...	X	...
		Field	...	...	...	X	...	...	X	...
Ethylene propylene rubber	XL	Factory	...	...	...	X	X	...	...	...
		Field	...	...	...	X	X	X	...	...
Low-density polyethylene	TP	Factory	...	...	...	X	...	...	X	...
		Field	...	...	...	X	...	X	X	...
Neoprene (polychloroprene)	XL	Factory	...	...	...	X	...	...	...	...
		Field	...	...	...	X	...	...	...	
Polyvinylchloride	TP	Factory	X	X	X	X	...	...	X	X
		Field	X	X	X	X	...	X	X	

*Source: Liner Materials Exposed to Municipal Solid Waste Leachate, Draft (EPA, 1982).
**XL = crosslinked or vulcanized; TP = thermoplastic.

6 ASPHALT AND ADMIXED MATERIALS AS LINERS AND COVERS

Characteristics

A variety of admixed materials can be formed in place to make a liner or cover, including asphalt, concrete, soil cement, soil asphalt, catalytically blown asphalt, and asphalt emulsions. Many of these materials can be sprayed in liquid form directly onto prepared surfaces. The liquid then solidifies to form a continuous membrane.

Hydraulic asphalt concretes (HACs) are hot mixtures of asphalt cement and mineral aggregate quite similar to highway paving asphalt concrete. Compaction of HAC can achieve a permeability coefficient less than 1×10^{-7} cm/sec. HAC also is resistant to plant growth and weather extremes. When applied to side slopes, it resists slippage and creep, and it is flexible enough to conform to slight deformation in the subgrade. Because inhomogeneities can result from inadequate mixing and compaction, liners should be greater than 10 cm thick to contain landfill leachates. The material should be compacted to less than 4 percent voids to obtain the low permeability needed for liners. When HAC is compacted to a voids content of less than 2.5 percent, a permeability of less than 1×10^{-9} cm/sec can be obtained.

Soil cement is a compacted mixture of Portland cement, water, and selected in-place soils. This mixture results in a low-strength Portland cement with permeability depending on the type of soil used. As expected, more granular soils produce a more permeable soil cement; however, permeability coefficients as low as 1×10^{-6} cm/sec have resulted from the use of fine-grained soil. Coatings such as epoxy asphalt and epoxy coal tar have been used to decrease soil cement permeability. Any inorganic, well-graded soil with less than 50 percent silt and clay can be used in soil cement. The soil should have a maximum particle size of 2 cm and a maximum clay content of 35 percent. The optimum moisture content is that which results in maximum density. Soil cement has the disadvantage of cracking and shrinking when it dries.

Soil asphalt is a mixture of on-site soil and liquid asphalt. The soil should be gravelly with low plasticity, and 10 to 25 percent silty fines. As with soil cement, the permeability varies with the percentage compaction and percentage asphalt. Cutback asphalt is not recommended for use in this mixture; also, asphalt emulsion is too permeable unless it is waterproofed with a hydrocarbon or bituminous seal.

A sprayed-on membrane commonly used for liners and covers is catalytically blown asphalt. This membrane is made from asphalt with a high softening point when air is blown through the molten asphalt in the presence of a catalyst such as phosphorus pentoxide or ferric chloride. The material is then sprayed onto a prepared surface at a 203.5°C temperature, a 3.45 bar pressure, and a 4.7-L/m^2 rate. Air-blown asphalt can be applied with mobile equipment in cold or wet weather. The finished membrane is usually .64 cm thick and is tough and flexible. When properly covered and protected from mechanical damage, it will last indefinitely. Studies have indicated that the addition of 3 to 5 percent rubber will improve the elasticity, toughness, and low temperature brittleness of the membrane and also make it more resistant to flow and aging. As with soil asphalt, the membrane must be waterproofed with a hydrocarbon or bituminous seal.

Membranes can also be constructed by spraying emulsions of asphalt in water at ambient temperatures (above freezing). The resulting membranes are weaker with lower softening points than hot, air-blown asphalt. However, to increase their toughness and dimensional stability, asphalt emulsions can be sprayed onto supporting fabrics. These fabrics can be woven jute, woven or nonwoven glass fiber, or nonwoven synthetic fiber.

Chemical Compatibility of Asphalt and Admixtures

Studies have been conducted using landfill simulators and various admixed liner materials. After 1 year of exposure to landfill leachate, asphalt concrete and soil asphalt lost much of their compressive strength; however, they maintained their impermeability. The asphalt binder appeared to absorb the organic components of the leachate and then soften.

In another study, soil cement lost some compressive strength, but it actually became more impermeable upon exposure to landfill leachate. The material also hardened with exposure to leachate.

Some admixed materials have been tested with a variety of industrial wastes. These wastes are listed in Table 16 along with a relative ranking of their compatibility with various liner and cover materials. Soil cement was tested with all except the acid waste. No seepage through the liner specimens was seen during 30 months of testing. After 625 days of exposure to the wastes, the specimens were tested for compressive strength. The compressive strength of the exposed specimen was greater than that of the unexposed specimen in all the wastes studied. An epoxy asphalt coating applied to one-half the surface of each specimen appeared to blister as a result of exposure to the industrial wastes.

HAC appeared to function satisfactorily with the pesticide and spent caustic wastes; however, it failed under the nitric acid waste. This failure was primarily a result of the calcium carbonate aggregate failing since the asphalt actually hardened considerably. When exposed to the lead waste the asphalt absorbed much of the waste's oily constituents and became "mushy" after a limited time. However, duplicate tests still in progress have not shown any seepage.

An asphalt emulsion applied over a nonwoven fabric was placed under pesticide, spent caustic, and lead wastes. The pesticide and caustic waste did not adversely affect the membrane; however, the gravel under the membrane with the lead waste was wet and stained, indicating some waste had seeped through the liner.

Installation of Asphalt and Admixed Material

Soil cement liners are usually placed using road paving methods and equipment. A recommended cement is type Portland V sulfate-resistant. Best results are obtained when a well-graded, sandy soil with maximum particle size

Table 16*

Liner Cover-Industrial Waste Compatibilities[a]

Liner/Cover Material	Caustic Petroleum Sludge	Acidic Steel-Pickling Waste	Electro-plating Sludge	Toxic Pesticide Formula-tions	Oil Refinery Sludge	Toxic Pharma-ceutical Waste	Rubber and Plastic
Soils							
Compacted clayey soils	P	P	P	G	G	G	G
Soil-bentonite	P	P	P	G	G	G	G
Admixes							
Asphalt-concrete	F	F	F	F	P	F	G
Asphalt-membrane	F	F	F	F	P	F	G
Soil asphalt	F	P	P	F	P	F	G
Soil cement	F	P	P	G	G	G	G
Polymeric membrane							
Butyl rubber	G	G	G	F	P	F	G
Chlorinated polyethylene	G	F	F	F	P	F	G
Chlorosulfonated poly-ethylene	G	G	G	F	P	F	G
Ethylene propylene rubber	G	G	G	F	P	F	G
Polyethylene (low density)	G	F	F	G	F	G	G
Polyvinylchloride	G	F	F	G	G	G	G

*W.S. Stewart, State-of-the-Art Study of Land Impoundment Techniques, EPA-600/2-78-196 (EPA, 1978).
[a]G = good, F = fair, P = poor.

2 cm is mixed with the cement. The design mix should be tested for moisture-density relationship, wet-dry and freeze-thaw properties, and permeability. The soil cement should not be placed at temperatures below 45°F (7°C). Compaction should proceed within 1 hr of spreading the mixture and the compacted density should be 98 percent of the laboratory maximum density. If more than one layer is placed, the first layer should be kept moist by fog spraying. The finished liner should be allowed to cure for 7 days. Soil cement should be sealed as soon as possible after compaction by spraying on bituminous liquids or emulsions.

Asphalt concrete used as a landfill liner is similar to paving asphalt concrete, but has a higher percentage of mineral filler and asphalt. This mix does not need to be as stable as that used for paving asphalt; however, it should be stable on side slopes (generally 2:1) when hot. As with synthetic membranes, the subgrade should be properly compacted to at least 95 percent the maximum density, smoothed, and treated to prevent weed growth. Hot liquid asphalt is then applied and allowed to cure to prime the surface for the asphalt concrete mix. The mix should be placed with spreaders capable of producing courses 3 to 5 m wide. Care should be taken to avoid grooves, depressions, or holes in the surface and to minimize the number of cold joints. The edges of each course should be smooth and sloped for 15 to 30 cm, then heated before forming the joint with the adjacent course. Slopes should be spread from bottom to top before paving the floor. The liner should be compacted as soon as possible after spreading and, if thicknesses greater than 7.6 cm are required, multiple courses with staggered joints should be used.

Sprayed on liners and covers require a more carefully prepared subgrade than other liner and cover membranes. Care must be taken in placing the material to make it pinhole free. If a smooth surface cannot be obtained with the subgrade, a fine sand or soil padding may be needed.

Catalytically blown asphalt is an example of a spray liner material. It is usually placed in three 1.54-L/m^2 layers to avoid pinholes, with a final membrane thickness of approximately .64 cm. Each layer should be overlapped 30 to 60 cm. Because of this material's rapid cooling and hardening properties, the second and third passes can be applied immediately after finishing the previous layer. These same properties can cause problems with the application equipment, however. To prevent asphalt hardening in the lines, the spray bars should not be turned off for more than 1 or 2 minutes at a time. Immediately after each spraying operation, all pumps, lines, and spray bars should be cleaned with air or distillate.

Asphalt emulsions are also sprayed onto surfaces. Unlike catalytically blown asphalt, time must be allowed between coats to avoid entrapped air and the resulting porosity.

7 EXAMPLES OF LINER AND COVER USE

Martone Landfill: Clay Liner

The Martone landfill is located in the scenic rural environment of Barre, MA. The area receives 92 cm or more of precipitation annually. As with most landfills in the New England area, limited quantities of clay are available. Clay is usually avoided for use as a cover, anyway, due to operational problems. For example, during the spring and similar wet periods, clay and other soils with fines become almost impossible to work with in a landfill operation. Refuse vehicles get stuck and heavy equipment used to excavate, spread, and compact the wet, tightly packed clays are overworked. Therefore, the material easiest to dig, haul, and spread is used for cover material. This more porous cover material reduces the "spring mud" problems, but infiltration and resulting leachate problems are amplified.

Faced with these environmental and operational problems, it was decided to use all available on-site clay for the liner and to avoid its use as cover material at the Martone landfill. The leachate would then be collected and treated. The fill area was constructed with a 1.3-m-thick clay liner and 3.6-m-high dikes on nearly all sides (Figure 6). An additional 1.3-m layer of natural cover was placed on the clay liner to avoid damage that could be caused by the landfill equipment. The leachate could then be contained and directed toward a 10.7-m gravel filter on the landfill perimeter. Sampling funnels were installed in the soil layer to study leachate movement under the refuse and in the clay liner to check for leakage.

After leachate leaves the landfill through the gravel dike, it flows into a catch basin. From the catch basin, it is directed through a series of PVC-lined lagoons. Asphalt liners were once used in the lagoons, but the asphalt appeared to inhibit the algal and bacterial growth that treats landfill leachate. During the years of operation, there has been no indication of leakage through the clay landfill liner. The only problem observed has been with the gravel filter plugging. No leachate attenuation has been seen as leachate passes through the 1.3 m of natural soil above the liner. During the years of operation and testing (90-day retention time), the clay liner and lagoon system have proven to be an effective leachate control and treatment system. The system has maintained about 99 percent treatment efficiency for biological oxygen demand, chemical oxygen demand, nutrients, and most metals.[18]

Lycoming, PA, Landfill: Membrane Liner

When this landfill was completed in June 1978, it represented the "state of the art" in sanitary landfills. It has a synthetic liner and operates with a leachate collection, aeration, and recycling system. The 8.1-ha site required the movement of 267,750 m^3 of dirt and the installation of a complete groundwater protection system consisting of about a 1,220-m length of 15.2-cm bituminous-coated, corrugated metal pipe. The next construction stage

[18] H. Dratfield, Northeast Consultants, Springfield, MA, registered architectural engineer, personal communication.

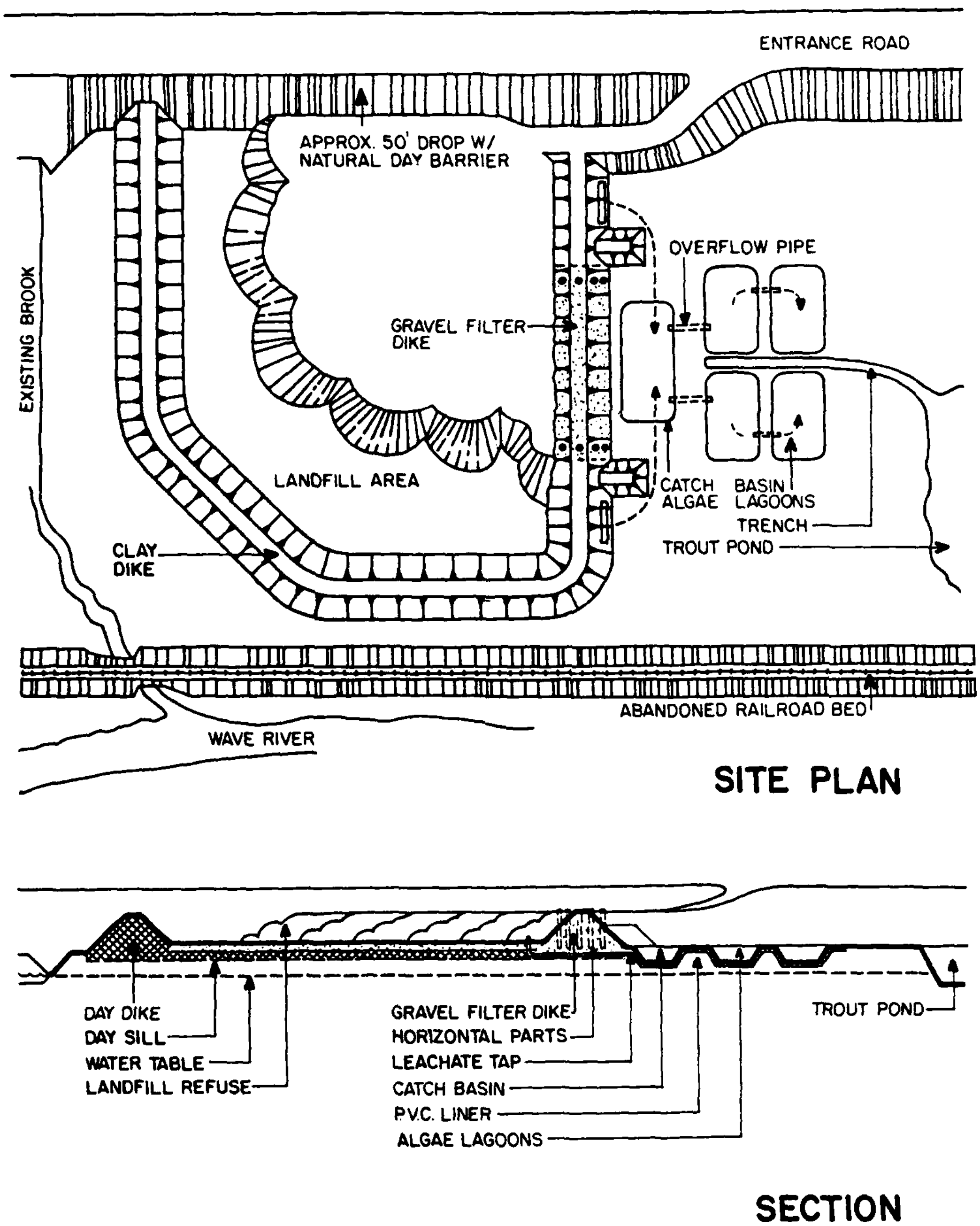

Figure 6. Schematic of Martone lined landfill. [From R. A. Shafer, E. D. Smith, J. T. Bandy, P. G. Malone, D. A. Moore, and L. W. Jones, Treatment of Landfill Leachate at Army Facilities, Technical Report N-155/ADA132483 (CERL, 1983).]

included spreading a 30.4-cm layer of fine filter sand to provide a base for the membrane liner. The liner was made of 20-mil (0.5-mm) PVC, arriving at the site in 21.4- by 128-m panels. The panels were field-spliced with a special adhesive. The membrane installation required approximately 6 months to complete and involved nearly a million square feet of 20-mil (0.5-mm) PVC liner material. An additional 3069 m^2 of 28-mil (0.7-mm) PVC membrane was used to line the leachate collection lagoon at the toe of the landfill.

The liner was covered with a 15.2-cm protective layer of sand, and a 30.4-cm layer of select native material was placed on top of the sand. Perforated pipe (15.2- and 20.3-cm) was installed in the sand layer to collect the leachate as it percolates through the refuse to the top of the liner. These pipes direct the leachate down-gradient to leachate manholes at the southern end of the landfill. The leachate then flows into the lagoon. In the lagoon, the leachate is constantly aerated, then is pumped back to the working face of the landfill and injected into 4.6-m-deep trenches in the compacted refuse.

As a precaution, the water collected in the landfill's groundwater system below the liner is sampled and analyzed daily. To date, there has been no indication of the liner failing.[19]

Winnebago County Land Reclamation Site: Asphalt Liner

In Rockford, IL, the problem of waste disposal without impact on local water quality has been solved by converting an abandoned gravel pit and rock quarry into a sanitary landfill that eventually will be reclaimed as a recreation area. The gravel pit and adjacent rock quarry were lined with a 5-cm-thick layer of asphalt. Before the lining was placed, the pit's bottom and side slopes were graded. Surface water and leachate flow toward a ditch at the toe of the fill area where they are collected in perforated pipes and stored in a 75,472-L steel tank. The tank's contents are then recirculated over the landfill, as needed.

The first part of the landfill liner was prepared using 5 cm of hot asphalt mix (200 to 300 penetration asphalt cement). An asphalt dike was constructed at the inside edge of each finished part to keep leachate from flowing into unlined areas of the gravel pit. The top of the liner was then sealed with a tar emulsion to protect it against naphtha or other solvents. A 15.2-cm layer of sand was then placed over the coated asphalt liner. The remaining portion of the gravel pit was lined with a 5-cm layer of asphalt cold-mix. This mixture was composed of crushed rock, sand, and 6 to 6.5 percent medium-setting cationic emulsified asphalt. The material was sealed with one application of .8 L/m^2 emulsified asphalt and two applications of .8 L/m^3 tar emulsion. A 15.2-cm layer of sand was also placed on top of this part of the liner. Four monitoring wells were installed on site to check for groundwater contamination. No leakage through either section of the liner has been detected.[20]

[19]"Lycoming County Solid Waste Facility Becomes a Reality," Constructioneer (July 17, 1978).

[20]A. D. Hill, "Line It and Put It to Use," Asphalt Water Control Environ. Preserv. (The Asphalt Institute, December 1973).

Lowell, MA, Landfill: Admixed Liner and Cap

At Lowell, MA, a new landfill was constructed on top of a completed 30-year-old landfill. The major construction problem was choosing a membrane material that could act as both an impervious cap to the already buried refuse and as a liner to the new refuse without cracking with settlement. The old landfill had a 13.7-m-thick layer of refuse and leachate drainage was not controlled. To eliminate leachate pollution from the old waste and allow landfilling of new refuse, several problems had to be solved:

- Eliminating any further infiltration of surface water into the old refuse

- Collecting leachate from the new refuse and preventing it from infiltrating the old refuse

- Constructing a cap/liner that would not crack from differential settlement caused by the buried refuse.

An admixed liner of prepared bentonite was used. Specifications called for the construction of a 30.4-cm-thick compacted liner, permeability 1×10^{-6} cm/sec, over the old refuse. Sixty-one centimeters of uncompacted waste was then placed on top of the liner. Since the bentonite/soil mixture never hardens, it remains flexible, naturally self-sealing any cracks that might develop from settlement. Figure 7 is a schematic of the landfill. Leachate is collected at the landfill toe in a lined, aerated lagoon. The contents of this lagoon are then pumped to a series of smaller, lined lagoons behind the landfill, and after the desired level of treatment has been achieved, are discharged through an infiltration lagoon. The liners for these lagoons were also constructed with bentonite/soil mixture. The liner specifications for the lagoons called for a permeability of 1×10^{-7} cm/sec.

As expected, once the impervious liner/cap was installed over the old refuse, lateral migration of landfill gas was detected in adjacent housing areas. A passive gas control system was installed using a gravel-filled trench with a PVC liner on the housing side. Methane concentrations immediately decreased in houses and shops adjacent to the landfill. Continual monitoring for both methane migration and groundwater contamination has been conducted with no off-site migration seen.[21]

Windham, CT, Landfill: Membrane Cap

The Windham landfill is a closed 10.1-ha facility that operated from about 1945 to 1978. The landfill was located in sand and gravel adjacent to a public water reservoir. Part of the landfill was constructed below the water table and local sands and gravels were used for cover material. Several monitoring points placed through and around the landfill defined the area of groundwater pollution.

[21] H. Dratfield and L. Mavtone, personal communication.

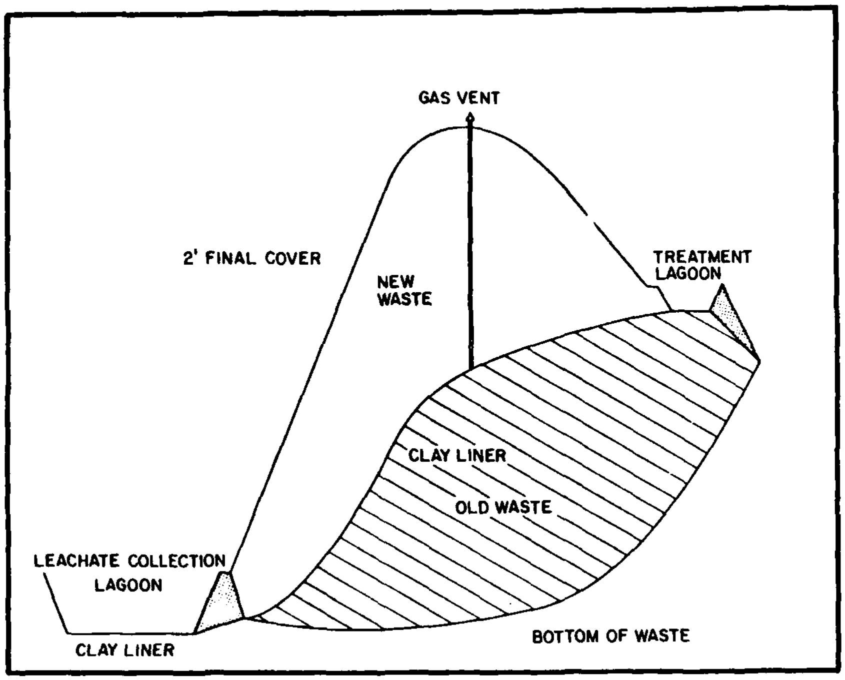

Figure 7. Lowell landfill liner and cap.

Before installing a cap, a detailed monitoring network was constructed to develop information on the landfill's reaction to precipitation before and after completion of the top seal. This network included:

- Suction and pan lysimeters in the refuse and surrounding soils
- Piezometers placed into the water table below and around the landfill
- Surface water sampling points.

A 20-mil (0.5-mm) PVC membrane cap was placed over the entire site. The sheets of PVC were solvent welded at the seams and placed on a 10-cm-thick layer of compacted, fine-grained sand washings. The membrane was covered with 45.7 cm of local, mixed fine sand and gravel which was spread in three layers. The area was then mulched and revegetated (Figure 8).

Approximately 6 months after installation of the membrane cap, seven test pits were excavated by hand to check the membrane material's integrity (Figure 9). Although there were several indentations up to 3.8 cm deep in the membrane, no punctures were evident. The cover thickness varied from 20.3 to 45.7 cm. Truck traffic during final cover spreading caused some areas to wear more than others. Several of these high-traffic areas were used to check the membrane cap's durability; again, no visible punctures were evident. One month later, sections of the membrane seal were removed from test pits 2 and 3. Several breaks were seen in the section from test pit 3 when it was held to the light. The maximum break was only 6.3 cm long, however. The section from test pit 2 had no breaks. It was concluded that, even in areas of heaviest truck traffic, there were only a few breaks in the membrane which did not greatly reduce the membrane's effectiveness in stopping the movement of water

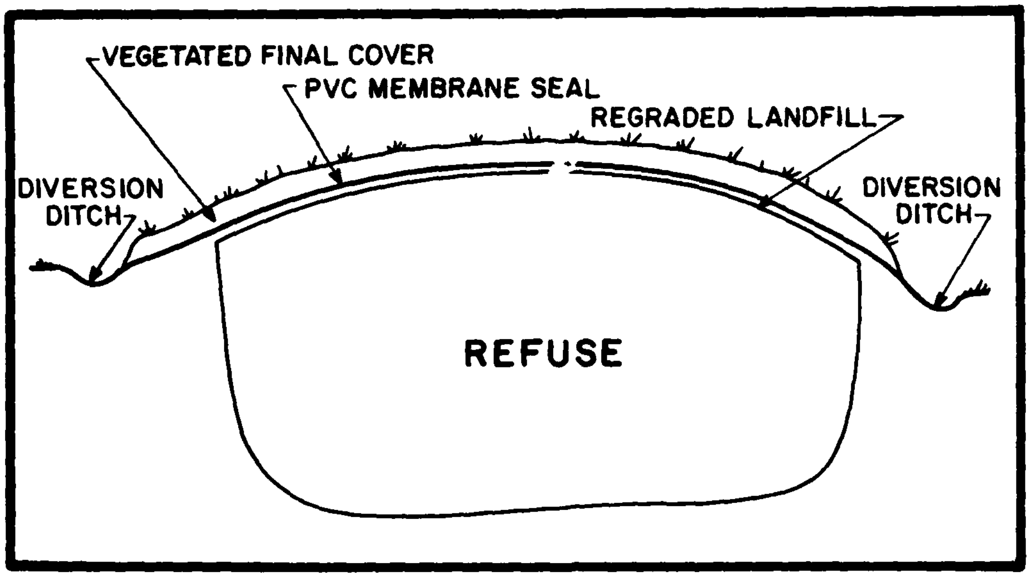

Figure 8. Typical section through Windham landfill. (From G. H. Emrich and W. W. Beck, "Top Sealing to Minimize Leachate Generation," Land Disposal: Hazardous Waste Proceedings of the Seventh Annual Research Symposium, EPA 600/9-81-006 [EPA, 1981].)

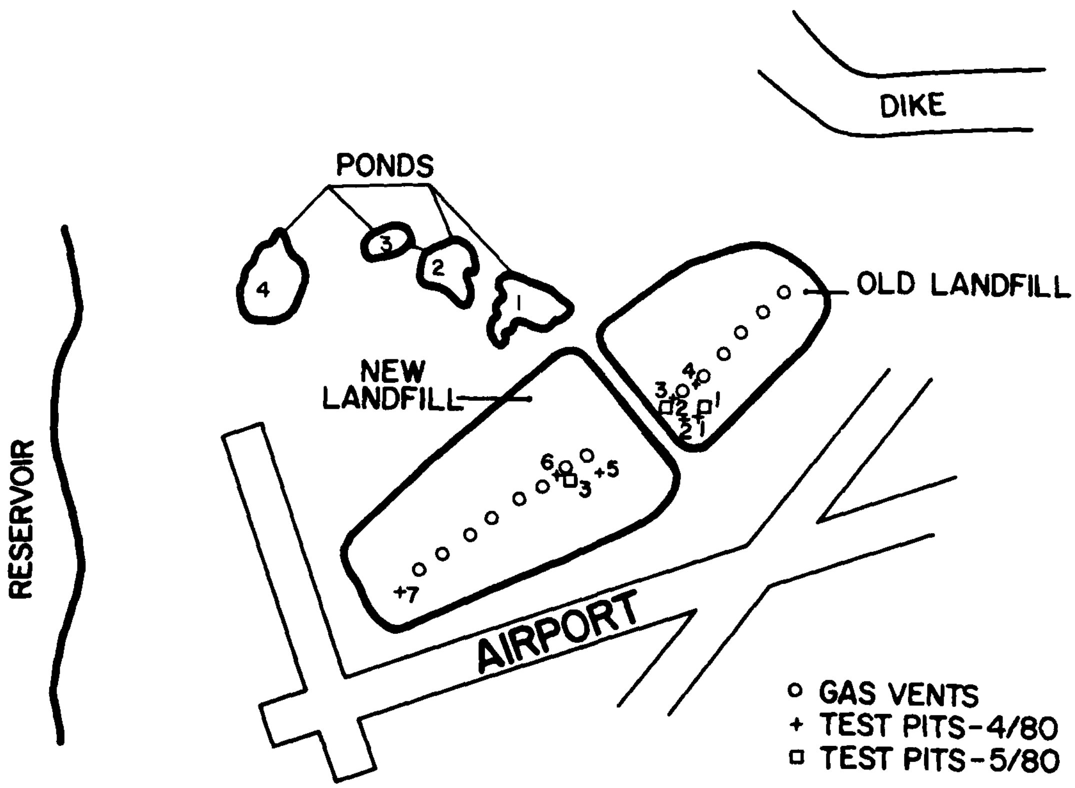

Figure 9. Location of test pits for top seal integrity tests. (From G. H. Enrich and W. W. Beck.)

through the cover. It was further concluded that the major volume of infiltrating water moved down to the membrane and then horizontally across the membrane surface to the edges of the refuse and into the lined drainage ditches.

Also before installing the cap, wells, ponds, and lysimeters installed in the landfill were sampled to estimate the amount of infiltration taking place. Water levels in the wells and the water volume in the pan lysimeters were measured weekly and correlated with daily precipitation data. Results indicated that, before membrane cap placement, as much as 85 percent of the water passing through the refuse came from precipitation infiltration.

After the membrane cap was installed, bimonthly sampling of the wells, ponds, and lysimeters continued. Pan lysimeters below the membrane seal had little or no water present after precipitation. Observation of the ponds adjacent to the landfill showed that coloration resulting from leachate contamination had been reduced greatly. Groundwater analysis indicated that the major contaminated plume, which was moving westward toward the reservoir, had been narrowed after top seal installation (Figure 10). The secondary plume, which was moving northward toward ponds 1, 2, and 3, had withdrawn toward the landfill as a result of installing the PVC membrane cap.

Based on these results, it has been concluded that a 20-mil (0.5-mm) PVC top seal can be placed successfully over an area as large as 10.1 ha. The membrane maintained its flexibility during placement of the cover material and showed only a few punctures in areas with high truck traffic. The membrane intercepted the precipitation that had been infiltrating the cover and directed it laterally to the diversion ditches along the edge of the landfill. As a result, the plume of contamination leaving the landfill is receding toward the landfill, and local contaminant concentrations are decreasing.[22]

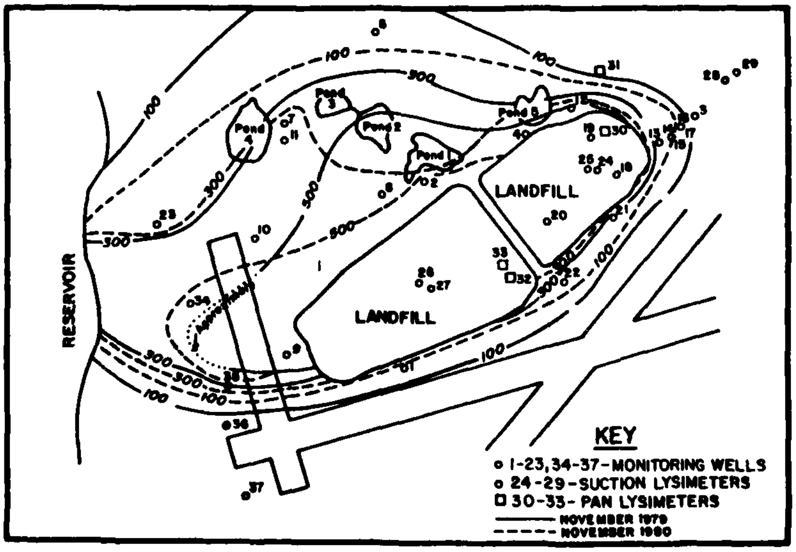

Figure 10. Leachate plume in November 1979 and November 1980. (From G. H. Emrich and W. W. Beck.)

[22]G. H. Emrich and W. W. Beck.

8 CONCLUSIONS

Low permeability materials used to cover and line Army waste disposal sites can prevent leachate production and migration to groundwater and surface water bodies. Such liners and covers can also prevent migration of waste gases outside the refuse boundaries.

The following points summarize the lessons learned from field use of the different liner and cover materials:

1. Factors such as the type of landfill gas control and the climate are important when selecting a liner or cover material.

2. Regardless of the material used, liner or cover success depends on the quality of work during installation of the control system.

3. Once in place, the cover or liner system's compatibility with the landfill environment becomes a major factor affecting service life. Compatibility applies to the chemical attack on a liner by the leachate as well as to the cover system's ability to accommodate settlement.

4. The lack of experience and long-term exposure of materials to various wastes demands careful monitoring of existing systems. This should be done by retrieving and inspecting sections of the liner or cover and by installing a groundwater and surface water monitoring system below and adjacent to the landfill site.

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APPENDIX:

POINTS OF CONTACT FOR OBTAINING ASSISTANCE

Several Army laboratories and agencies can help the facility engineers (FEs) and Major Commands choose and install leachate control systems. Points of contact and brief descriptions of the services provided follow.

U.S. Army Construction Engineering Research Laboratory (CERL)

Since 1978, CERL has been involved with research in cooperation with WES to evaluate the technical and economic aspects of sanitary landfill leachate and gas control at military installations using preventive and remedial measures. CERL is also tasked with developing ana pilot testing selected short- and long-term methods for controlling and treating leachate from both abandoned and operating sanitary landfills. Reports have been prepared providing guidance to MACOMs, Districts, and FEs. CERL has also begun a "Small Problems Program" through which Army personnel can ask for 16 hours of free assistance to help identify or solve Army-related leachate or gas problems.

For more information, contact CERL, P.O. Box 4005, Champaign, Il 61820; phone: Commercial 217-352-6511, FTS 958-7232, or Autovon through Chanute AFB. Point of contact is Dr. Edgar Smith, team leader of the Water Quality Management Team.

U.S. Army Environmental Hygiene Agency (AEHA)

The Solid Waste Branch, AEHA, helps Department of Defense (DOD) installations evaluate existing and proposed solid waste management programs with two major services: (1) on-site evaluation of present sanitary landfill operation techniques, and (2) hydrogeologic and soils analysis for recommending new sanitary landfill sites, as required for obtaining a State sanitary landfill permit. In addition, AEHA will locate and install monitoring wells up to 120 ft (36 m) deep to determine groundwater contamination from leachate. Soil samples are analyzed at Aberdeen Proving Ground, MD, for permeability, density, soil classification according to the Unified Soil Classification System, specific gravity, cation exchange capacity, and other properties.

These services can be requested by the installation MACOM through the Commander, U.S. Army Health Services Command, Attn: HSPA-P, Fort Sam Houston, TX 78234, with an information copy to Commander, U.S. Army Environmental Hygiene Agency, Attn: HSE-ES, Aberdeen Proving Ground, MD 21010. The Commander, U.S. Army Health Services Command will endorse the request with recommended action to the AEHA, which will program requests, by priority, fiscal year, and quarter. All written requests should include an installation point of contact and telephone number.

Telephone consultation can be obtained by contacting Chief, Groundwater and Solid Waste Branch, Autovon 584-2024, commercial 301-671-2024.

U.S. Army Waterways Experiment Station (WES)

WES has been involved in several research projects to evaluate problems associated with the generation of leachate and gas in landfills. In cooperation with the EPA, WES has examined the leachate from mixed hazardous industrial and municipal wastes and conducted extensive field investigations on power generation wastes, municipal landfills, and industrial waste landfills. WES has also conducted field gas surveys and established three gas and leachate monitoring systems at Fort Belvoir, VA. In cooperation with CERL, WES is setting up two pilot-scale leachate treatment systems. WES is also doing a design study on a gas control system for closed landfills.

WES has an extensive information base on landfill design, leachate and gas control, and hazardous waste disposal. More than 30 publications on municipal and hazardous waste disposal technology have been generated from the EPA- and Army-sponsored research at WES.

Point of contact: Mr. Norman R. Francingues, P.O. Box 631, Vicksburg, MS 39180, commercial 601-634-3960, FTS 542-3960.

U.S. Army Toxic and Hazardous Materials Agency (USATHAMA)

USATHAMA conducts installation assessments to search for, identify, and assess actual or potential chemical, biological, or radiological contamination or migration by reviewing records and interviewing present and former employees. The agency also conducts installation environmental contamination surveys to establish contamination levels and verifies whether there is migration by determining subsurface water movement patterns.

USATHAMA is the major DOD agency for developing pollution abatement/containment technology for migrating contaminants and for contamination problems on excess properties. The agency also has design and process engineering expertise in these areas.

USATHAMA has developed a data management system for environmental contamination at assigned Army installations. Computer mapping of sampling points, groundwater head, chemical concentration contours, and borelog profile are provided by interactive programs. In addition to the reduction of raw data, USATHAMA can provide bibliographic searching of open literature databases. Chemical and physical properties of compounds can be obtained through telecommunication links with the National Institute of Health and with the EPA. The agency maintains a registry of contamination from past operations at a summary level for each assigned Army installation.

Point of contact: Andy Anderson, Aberdeen Proving Ground, MD 21010, DRXTH-A, commercial 301-671-3618, Autovon 584-3618.

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